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THESIS

SURFACE PIERCING PROPELLER PERFORMANCE

by

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September 2005

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This thesis addresses possible improvements in the efficiency (thrust) of surface piercing propellers; in particular with respect to the angle of the propeller shaft came to mind. Preliminary calculations based on the basic pitch/diameter geometry suggest that about 3-5% efficiency is lost if the shaft is parallel to the flow, compared to skewed a few degrees in the "paddlewheel" direction at certain speeds. More accurate calculations based on the lift characteristics of each blade, on the angle of attack and the flow of water over each blade and given a set of basic assumption on the over all performance of each blade, as the blade enters and leaves the water; are used to determine the increase in efficiency. Full scale experimental results are also presented in support of the calculations.

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SURFACE PIERCING PROPELLER PERFORMANCE

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ABSTRACT

This thesis addresses possible improvements in the efficiency (thrust) of surface piercing propellers; in particular with respect to the angle of the propeller shaft. Preliminary calculations based on the basic pitch/diameter geometry suggest that about 3-5% efficiency is lost if the shaft is parallel to the flow, compared to skewed a few degrees in the "paddlewheel" direction at certain speeds. More accurate calculations based on the lift characteristics of each blade, on the angle of attack and the flow of water over each blade and given a set of basic assumption on the over all performance of each blade, as the blade enters and leaves the water; are used to determine the increase in efficiency. Full scale experimental results are also presented in support of the calculations.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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Dedicated to my parents and my sister

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I. INTRODUCTION

A. BACKGROUND

The function of a propeller is to convert engine power output into thrust propulsion for a marine vessel. The position, shape and operating environment of the propeller on a boat hull has gone through many design changes. One major design change is the concept of surface piercing and semi-submerged propellers. In 1864 US Patient Publication Number: 00043522 Mr. O.C. Phelps of New York N.Y. improved the location of the propeller to keep it out of harms way by only having it in the water half of the time. The 1985 US Patient Publication Number 757043, Howard Arneson for San Rafael CA adapted that old design into a practical racing boat configuration now called "Surface Piercing Propellers. This thesis will provide an operating mode for surface piercing propellers that prove there is an increase in thrust beyond the performance limitations of a fixed pitch propeller. Designers and naval architects have been grappling with multiple aspect of the propulsion-by-propeller problem for generations. The Surface Piercing Propeller has provided a challenge to even the most sophisticated computer simulations. The results have been the evolution of a well known set of standard and efficient solutions to numerous Propulsion designs and problems.

When a new and promising solution to a propulsion problem appears, it's usually made possible by advancements in other closely related technology - material science, full scale testing, or by added controls and instrumentation devices. In the case of surface piercing propellers, the cause of change was to keep up with the advancements of off-shore racing hull technology combined with engines technology.

Innovative changes are often a result of hands on experimentation not just computational analysis. The Surface-piercing propeller engineering analysis is complicated by the mixed media environment of air & water. The fully immersed propeller analysis is well understood through principles of fluid dynamics and hydraulics. The air media propeller likewise is an integral part of aviation studies and airfoil analysis. These analysis techniques are significantly different resulting in very few common techniques for the mixed media analysis. At best techniques used are much more complex

than simply changing density or using compressibility in a mixed ratio mode. Surface Piercing Propeller propulsion is coming close to its performance limits. Surface Piercing Propellers require an extremely large computational capability to be understood so it is not available to the average innovator or naval architect. So it is understandable that there is skepticism with the idea of using surface-piercing propellers on more-or-less conventional craft in the boatbuilding community.

Surface-piercing propellers look and operate much like fully submerged propellers at slower speed. However, they are specially designed to operate only half in the water and half out of the water at high speeds. The surface-piercing mode of the propeller, surface propeller or partially submerged propeller is a propeller that is positioned so that when the vessel is underway the waterline passes through the propeller's hub. Howard Arneson’s innovation was to extend the propeller shaft straight through the transom of the vessel and locating the propeller some distance aft of the transom. At slower speeds the hull is usually pitched up putting the propeller in a fully submerged mode. This configuration lasts until the vessel’s velocity exceeds it’s hull speed. The vessels is now operating horizontally just on the water surface. The propeller is now rotated upward to ideally be half in and half out of the water. The relatively flattened water surface that flows out from the transom's bottom edge will provide a surface to pierce by each blade for half of each revolution. The An In the case of articulated surface drive systems, the propeller shaft is driven through a double universal joint inside an oil-tight ball joint, allowing the shaft to rotate for steering and to trim up and down for control of propeller submergence. Fixed-shaft surface drives can use conventional shafts and stern tube bearings, but require rudders. In many racing applications, outboards and outdrive’s can be positioned sufficiently high on the vessel for the propellers to operate in a surface-piercing mode.

The Outboard motor application is much the same, however, the propeller is closer to the transom and may need to be raised up out of the water by hydraulic or a mechanical lifting mechanism. The hub on an outboard may require that the blade be lifted up even higher than an Arneson drive. The impact is less blade contact with the water in a given revolution. The important operating feature is that each propeller blade is out of the water for half of each revolution.

The reason for skepticism and difficulty applying the Surface piercing mode is because of the analytical problem of the mixed media: air & water or both as a variable fluid media. A propeller blade foil is easier to optimize if it operates continuously in the smoothest most predictable possible flow. The surface piercing mode is the ever changing media of splashing through the water surface with each revolution. But nature can play tricks on our intuition. Sometimes an unsteady process is actually having more efficient potential than its continuous counterpart.

But to understand the discussion of Surface Piercing propellers, one must understand Cavitation. (Fig. 6&7) Cavitation is the formation of partial vacuums in a liquid by a swiftly moving solid body (hydrodynamic cavitation) or by high-intensity sound waves (acoustic cavitation). A Research study done by Yin Lu Young at UT studied and discusses the effect of hydrodynamic cavitation, which occurs when pressure drops below the saturated vapor pressure, consequently resulting in the formation of gas filled or gas and vapor filled bubbles (or cavities) [Batchelor 1967]. A common phenomenon known as boiling also describes the phase change from liquid to vapor. Boiling is different from cavitation in that it is driven by increase in temperature, instead of decrease in pressure. Cavitation can occur in any hydrodynamic device that operates in liquid. Cavities form in areas of low pressure and are often harmless. (Fig. 8) However, serious structural damage and/or decrease in device efficiency may occur when the cavities collapse. During the collapse, a long thin jet with velocity between 100 and 200 m/s develops and directs toward the solid surface it is in contact with [Lauterborn and Bolle 1975]. If this action is continuous and has a high frequency, it could even damage high quality steel. The effect of cavitation on propellers was first investigated by [Reynolds 1873] in the laboratory, and by [Parson 1897] and [Barnaby 1897] using full scale trials of the destroyer Daring. They found that the formation of vapor bubbles on the blades reduced the power of the propeller. Later investigators also found that cavitation can lead to undesirable effects such as blade surface erosion, increased hull pressure fluctuations and vibrations, acoustic energy radiation, and blade vibration. Thus, in the past, the goal in the design of propellers was to avoid cavitation. However, as stated in [Allison 1978], few propellers in practice can operate entirely without cavitation due to the non-axisymmetric inflow or unsteady body motion. Furthermore, propellers

without cavitation would need to be larger and slower than necessary [Allison 1978]. Application of cavitation-resistant propeller materials (e.g. titanium alloys or stainless steels) or coatings (e.g. elastomeric covering systems or epoxide formulations) can be used to reduce cavitation and erosion damage [Angell et al. 1979; Allison 1978; Foster 1989]. Nevertheless, the presence of cavitation is difficult to avoid at very high speeds. Thus, the development of reliable, versatile, and robust computational tools to predict propeller cavitation for general blade geometries is crucial to the design and assessment of marine propulsors. (Fig. 10) [Young Y]

A type of cavitation that is very common on marine propulsors is sheet cavitation. It is characterized by a "continuous" liquid/vapor interface which is "attached" to the blade surface. Sheet cavitation is further divided into two main categories: partial cavitation and supercavitation. A partial cavity is a cavity that is shorter than the chord length of the blade, such as shown in Fig. 1.3. A supercavity, on the other hand, is a cavity that is longer than the chord length of the blade, such as shown in Fig. 1.4. Other types of cavitation which can also occur include cloud and bubble cavitation. Tip and hub vortex cavitation are also very common for propellers. A general description on the different types of cavitation can be found in [Kato 1996].

In Yin Lu Young's study, the cavity on a propeller blade is treated strictly as sheet cavitation. She states the pressure inside the sheet cavity is assumed to be constant and equal to the vapor pressure. The rationale behind using the sheet cavity model includes: It provides a relatively simple mathematical model where potential flow theory can be applied. [Tulin 1980] found that sheet cavity is the first-order contributor to dynamically varying blade loads; and other forms of cavitation (such as tip or hub vortex cavitation) and other neglected phenomena (such as wake roll-up) can be added as refinements to the current models.

One Main difficulty in the analysis of sheet cavitation is determining the cavity surface (i.e., free streamline) where the pressure is prescribed. The problem is nonlinear because the extent and thickness of the cavity is unknown. In this work, the cavity surface is determined in the framework of a moving mixed boundary value problem. For a given cavitation number, the extent and thickness of the cavity surface at a given time

step is determined in an iterative manner until both the prescribed pressure and flow tangency condition are satisfied. In addition to cavitation, another common phenomena for hydrofoils and propellers is ventilation. Ventilation occurs when surface air or exhaust gases are drawn into the lifting surface. To help explain the difference between cavitation and ventilation, a schematic diagram showing a supercavitating hydrofoil, a ventilated hydrofoil1, and a surface-piercing hydrofoil is presented. Notice that the pressure on the ventilated surface is constant but equal to a value that is different from the vapor pressure. Therefore, the ventilated surface can be modeled like a cavity surface but with a different prescribed pressure. Moreover, the same method can be used to determine the flow detachment locations, as well as the extent and thickness of the ventilated surfaces. [Young Y]

B. THESIS DISCOVERY

The research for this thesis started back 15 years ago on the Indian River in Cocoa, Fl. Working at a local propeller refurbishing shop I learned how to build and modify numerous propellers configurations for various hull designs. The different propeller designs and blade modifications were used to provide greater thrust but were often different and unique for each hull or operators needs. Realizing the shape and size of the blade performed differently helping me to understand the basic fundamentals for basic propeller design. The learning process was easy, make changes to the propeller until you acquire the proper end result or performance was complicated by the trial and error process. After modification of many propellers, I started to learn how each change made a difference in performance.

C. SURFACE PIERCING PROPELLERS

Propeller Efficiency: Traditional propeller design and selection is almost always an exercise in trading off diameter against several other performance-limiting parameters. Basic momentum theory tells us that for a given speed and thrust, the larger the propeller, the higher the efficiency. While there are exceptions, most notably the effects of

frictional resistance on large, slow-turning propellers, it is generally borne out in practice that a larger propeller with a sufficiently deep gear ratio will be more efficient than a small one.

A number of design considerations conspire to limit the maximum feasible propeller diameter to something considerably smaller than the optimal size. These include blade tip clearance from the hull, maximum vessel draft, shaft angle, and engine location. While this may at times make life easy for the designer - the propeller diameter specified is simply the maximum that fits - it can also result in a considerable sacrifice of propulsive efficiency. And if these geometric limits on propeller diameter are exceeded, the result can be excessive vibration and damage due to low tip clearances, or a steep shaft angle with severe loss of efficiency and additional parasitic drag, or deep navigational draft that restricts operation or requires a protective keel and its associated drag. In many cases, the best design solution is to live with a mix of all of the above problems to some degree.

The surface-piercing propeller frees the designer from these limitations. There is virtually no limit to the size of propeller that will work. The designer is able to use a much deeper reduction ratio, and a larger, lightly-loaded, and more efficient propeller.

Surface-piercing which can be called partially submerged propeller is a special type of supercavitating propeller which operates at partially submerged conditions. Surface-piercing propellers are more efficient than submerged supercavitating propellers due to the reduction of appendage drag due to shafts, struts, propeller hub, etc. being out of the water or flow path. Appendage Drag: Exposed shafts, struts, and propeller hubs all contribute to parasitic drag. Inclined the exposed shafts not only produces form and frictional drag, but there is also induced drag associated with the magnus-effect lift caused by their rotation. There is a surprising amount of power loss resulting from the friction of the shaft rotating in the water flow. In fact, for conventional installations a net performance increase can often be realized by enclosing submerged shafts in non-rotating shrouds, despite the increase in diameter. Also reduction of blade surface friction and erosion since cavitation is replaced by ventilation. With each stroke, the propeller blade brings a bubble of air into what would otherwise be the vacuum cavity region. The

water ram effect that occurs when a vacuum cavity collapses is suppressed, because the air entrained in the cavity compresses as the cavity shrinks in size. Although the flow over a super ventilating propeller blade bears a superficial resemblance to that over a supercavitating blade, most of the vibration, surface erosion, and underwater noise are absent. [Young Y]

In theory there is a slight performance penalty for allowing surface air into the low-pressure cavities. Instead of near-zero pressure on the forward side of the blades, now there is 14.7 psi pushing backwards. But in practice, this effect is not significant considering the total thrust pressures involved in high-speed propellers.

Note that cavitation can also be associated with sudden loss of thrust and high propeller slip, often caused by a sharp maneuver or resistance increase. (Fig. 6) This can still occur with surface propellers, although the propeller is ventilating rather than cavitating and the result is not as damaging. A comparison of the maximum installed efficiency for different propulsors (taken from [Allison 1978]) is shown in (Fig. 7&9) According to [Hadler and Hecker1968], the first U.S. patent for a surface-piercing propeller was issued in 1869 to C. Sharp of Philadelphia. It was designed for shallow-draft boat propulsion. As time progressed, surface-piercing propellers were also used for hydroplane boats, and later for high-speed surface effect ships [Allison 1978]. In 1976, a large scale experiment, U.S. Navy SES-100B, confirmed that partially submerged propellers can achieve efficiencies comparable to fully submerged propellers [Allison 1978]. That experiment involved the use of an 100-ton surface effect ship propelled by two partially submerged controllable-pitch propellers at speeds up to 90 knots [Allison 1978]. Due to the superior propulsive characteristics of surface-piercing propellers, they are extensively used today in offshore racing, where speeds often exceed 100 knots [Olofsson 1996]. Recently, the commercial marine industries have shown an increased interest for large surface-piercing propellers. They are to be used in the next generation ferries with service speeds in the range of 70 to 80 knots at shaft powers of about 20 MW [Olofsson 2001]. Hence, there is a high demand from the marine industry to develop a reliable method that can predict the performance of surface-piercing propellers. In the past, the design of surface-piercing propellers often involved trial and error procedures using measured performance of test models in free-surface tunnels or towing tanks.

However, most of the trial-and-error approaches do not provide information about the dynamic blades loads nor the average propeller forces [Olofsson 1996]. Model tests are extremely expensive, and often hampered by scaling effects [Shen 1975] [Scherer 1977] and influenced by test techniques [Morgan 1966] [Suhrbier and Lecoffre 1986]. Numerical methods, on the other hand, were not able to model the real phenomena. Difficulties in modeling surface-piercing propellers include:

- Insufficient understanding of the physical phenomena at the blade’s entry to, and exit from, the free surface.
- Insufficient understanding of the dynamic loads accompanying a propeller piercing the water at high speed.
- The modeling of water jets and associated change in the free surface elevations at the time of the blade’s entry to, and exit from, the free surface.
- The effect of blade vibrations due to the cyclic loading and unloading of the blades associated with the blade’s entry to, and exit from, the free surface.

D. OBJECTIVE

The Objective of this thesis is to address the possible improvements in the efficiency (thrust) of surface piercing propellers; in particular with respect to the angle of the propeller shaft. Preliminary calculations based on the basic pitch/diameter geometry suggest a positive efficiency change if the shaft moves from parallel to the flow to a Yaw angle of a few degrees. The further complication of the thesis is that by rotating the drive shaft in the "paddlewheel" direction the simplified 2 dimensional analyses and air-foil performance processes move become mixed with flat plate flow theory. More accurate calculations based on the lift characteristics of each blade, on the angle of attack and the flow of water over each blade and given a set of basic assumption on the over all performance of each blade, as the blade enters and leaves the water; are used to determine the increase in efficiency and thrust . Full scale and computer experimental results are also presented in support of the calculations.

E. ORGANIZATION

This Thesis is organized in to three parts: Introduction (Chapter I), Surface Piercing Propellers (Chapter II), and Conclusions (Chapter III). A review of previous works, formulation, numerical implementation, convergence and validation studies, and results are presented in Chapter II. A systematic 2-D study of surface-piercing propellers and partially submerged using the exact free surface boundary conditions is also presented in Chapter II. Finally, the overall summary, discussions, conclusions, and recommendations for future research are presented in Chapter III.

Nomenclature

Latin Symbols

C_p	pressure coefficient, $C_p = (P - P_o)/(0.5\rho n^2 D^2)$
D	propeller diameter, $D = 2R$
f_{max}/C	maximum camber to chord ratio
F_{nD}	Froude number based on V_A, $F_{nD} = V_A/\sqrt{gD}$
F_r	Froude number based on n, $F_r = n^2 D/g$
g	gravitational acceleration
G	Green's function
h	cavity thickness over the blade surface, or blade tip immersion for partially submerged propellers
h_{sr}	cavity thickness over the separated region
h_w	cavity thickness over the wake surface
J_A	advance ratio based on V_A, $J_a = V_A/nD$
J_s	advance ratio based on V_s, $J_s = V_s/nD$
K_{Fx}, K_{Fy}, K_{Fz}	dynamic blade force coefficients in ship fixed coordinates
K_{Mx}, K_{My}, K_{Mz}	dynamic blade moment coefficients in ship fixed coordinates
K_Q	torque coefficient, $K_Q = Q/\rho n^2 D^5$
K_T	thrust coefficient, $K_T = T/\rho n^2 D^4$

Figure 1. Nomenclature Latin

l	cavity length
l_{sr}	separated region length
n	propeller rotational frequency (rev/s)
P	pressure
P_{atm}	atmospheric pressure
P_o	pressure far Upstream, at the propeller axis
P_v	vapor pressure of water
$\vec{q}$	total velocity
$\vec{q}_c$	total cavity velocity
$\vec{q}_{in}$	local inflow velocity (in the propeller fixed system)
$\vec{q}_w$	wake inflow velocity (in the ship fixed system)
Q	propeller torque
r	radius of propeller blade section
R	propeller radius
R_n	Reynolds number, $R_n = nD^2/\nu$
$\vec{s}, \vec{v}, \vec{n}$	non-orthogonal unit vectors along the local grid directions
S_B	blade surface, $S_B = S_{CB} + S_{WB}$
S_C	cavitating surface, $S_C = S_{CB} + S_{CW}$
S_{CB}	cavitating portion of blade surface
S_{CW}	cavitating portion of wake surface
S_F	free surface
S_∞	infinite boundary surface for foil entry problem
S_{WB}	wetted portion of blade surface
S_W	wake surface

Figure 2. Nomenclature Latin

t	time
T	propeller thrust
T_{max}/C	maximum thickness to chord ratio
T_{TE}/C	trailing edge thickness to chord ratio
$\vec{V}$	velocity of 2-D surface-piercing hydrofoil
V_A	advance speed of propeller, or
	inflow speed for 3-D hydrofoil
V_s	ship speed
W_n	Webber number, $W_n = nD/\sqrt{\sigma_k/\rho D}$
x, y, z	propeller fixed coordinates
x_s, y_s, z_s	ship fixed coordinates
XSR	separated region length to chord ratio

Figure 3. Nomenclature Latin

Greek Symbols

α	angle of attack for 3-D hydrofoil
β	shaft yaw angle
η	vertical coordinate of free surface
δ	cavity trailing edge thickness
δ_{sr}	separated region trailing edge thickness
Δt	time step size
$\Delta\theta$	blade angle increment, $\Delta\theta = \omega\Delta t$
η_p	propeller efficiency, $\eta_p = \frac{K_T}{K_Q}\frac{J_s}{2\pi}$
γ	shaft inclination angle
λ	ratio of full-scale diameter to model-scale diameter
ω	propeller angular velocity
ν	kinematic viscosity of water
ϕ	perturbation potential
Φ	total potential
ψ	angle between $\vec{s}$ and $\vec{v}$
ρ	fluid density
σ_k	capillarity constant of water
σ_n	cavitation number based on n, $\sigma_n = (P_o - P_v)/(0.5\rho n^2 D^2)$
σ_v	cavitation number based on V_A, $\sigma_v = (P_o - P_v)/(0.5\rho V_A^2)$
ζ	horizontal coordinate of free surface

Figure 4. Nomenclature Greek Symbols

Acronyms

BEM	boundary element method
CPU	central processing unit (time)
DTMB	David Taylor Model Basin
MIT	Massachusetts Institute of Technology
NACA	National Advisory Committee for Aeronautics
RAE	foil sections designed by [Treadgold et al. 1979]
VLM	vortex-lattice method

Computer Program Names

MPUF-3A	cavitating propeller potential flow solver based on VLM
PROPCAV	cavitating propeller potential flow solver based on BEM

Superscripts

$+$	upper cavity, separated region, or wake surface
$-$	lower cavity, separated region, or wake surface

Figure 5. Nomenclature

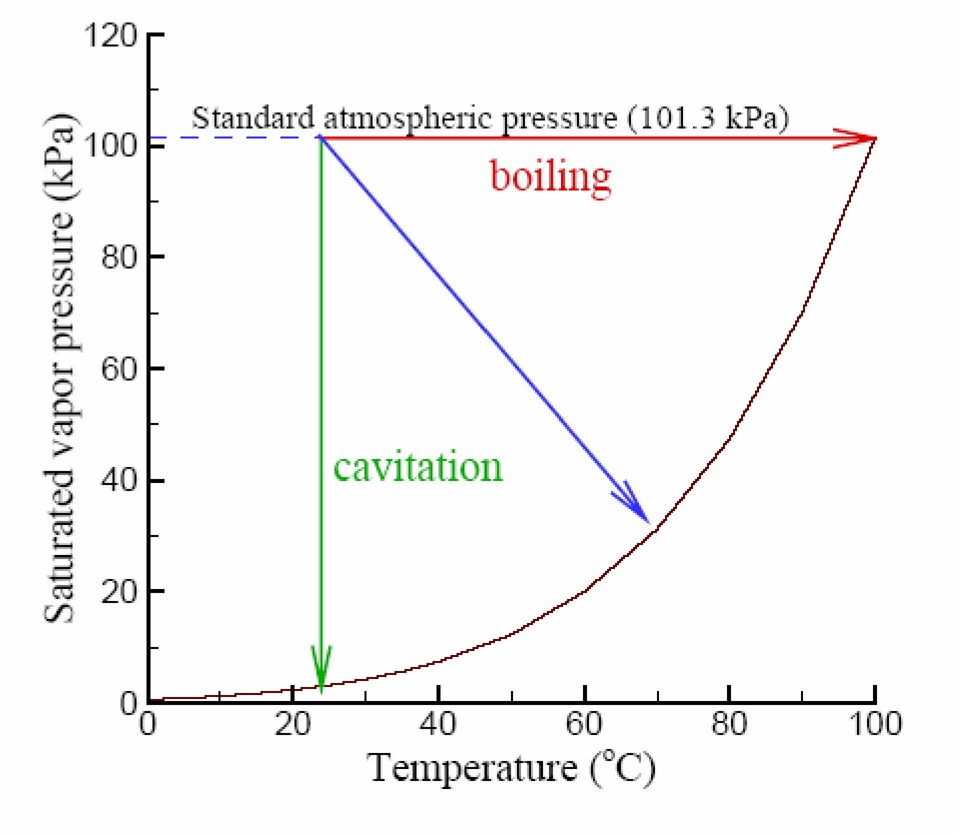

Figure 6. Saturated Vapor pressure of Water

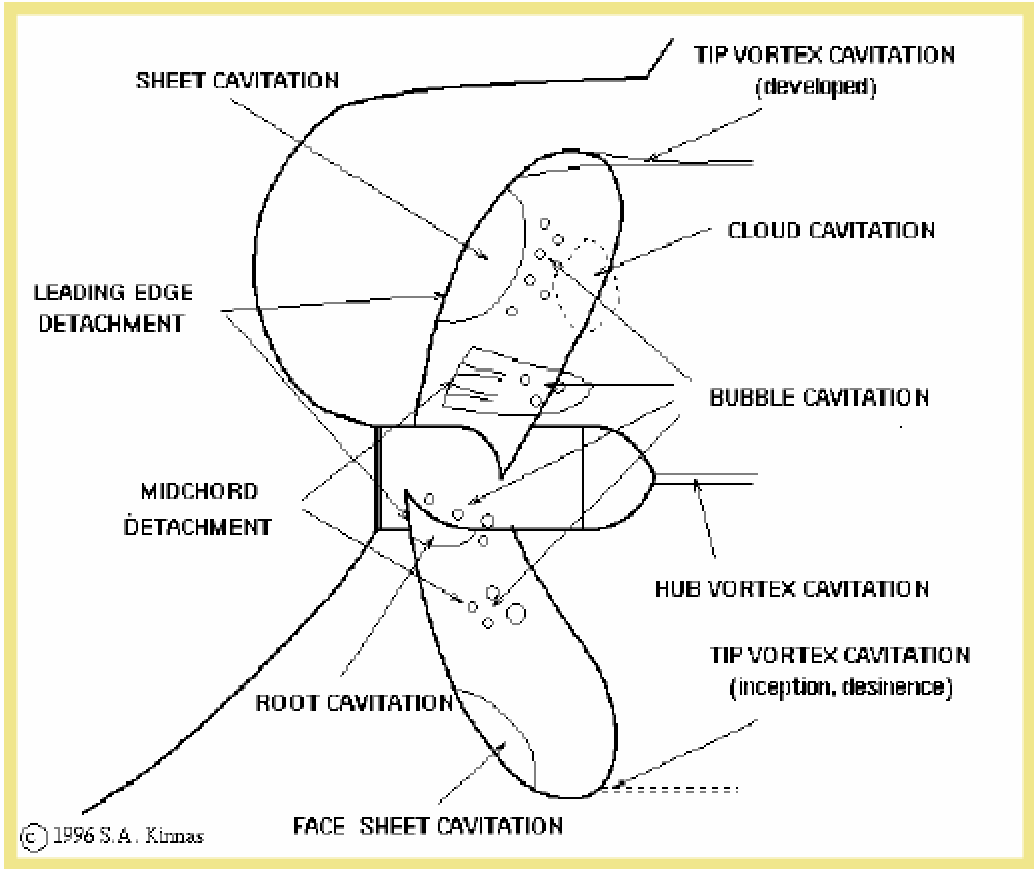

Figure 7. Different types of cavitation on marine propellers Taken from [Kinnas 1998]

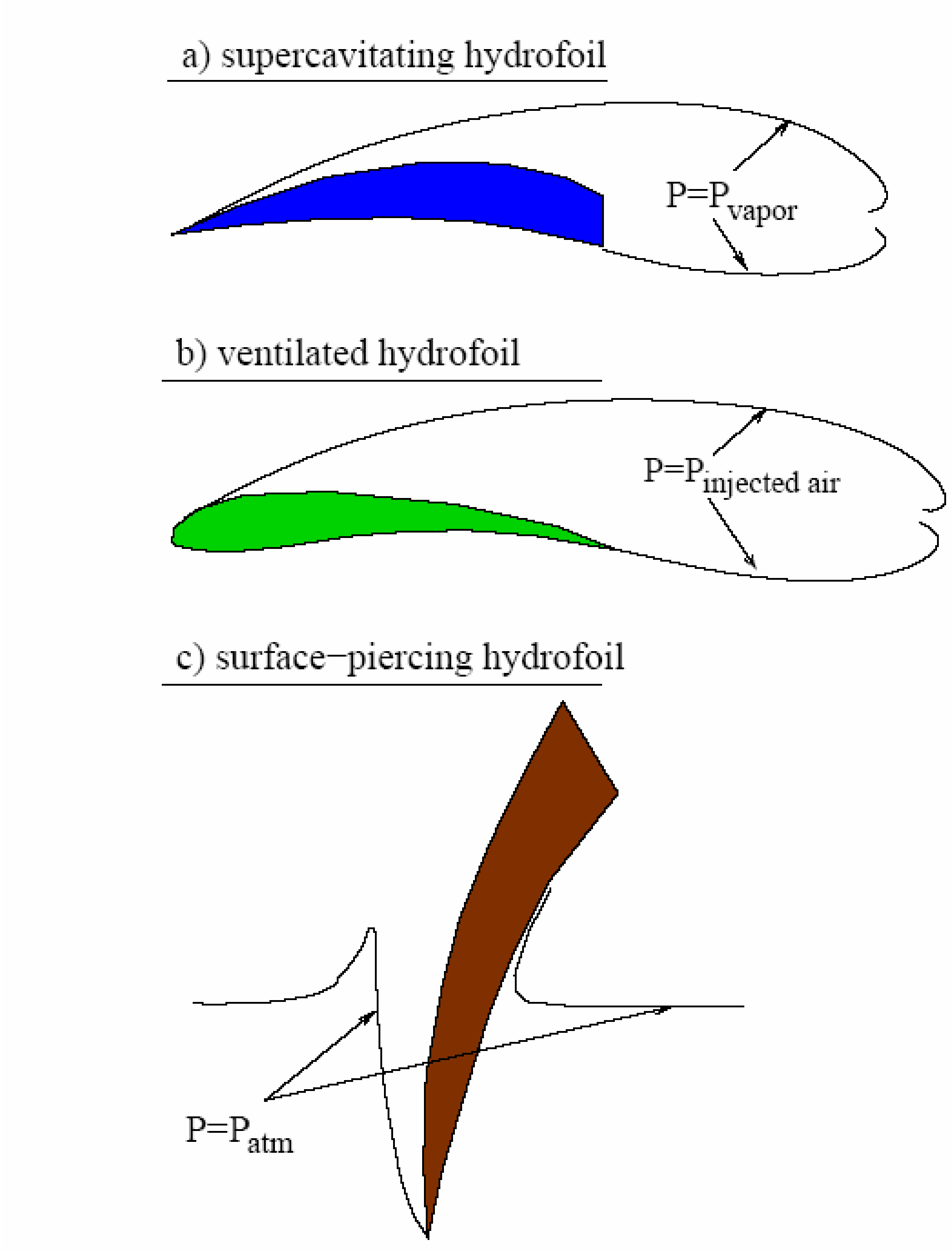

Figure 8. Graphical illustration of Supercavitating hydrofoil, a ventilated hydrofoil, and a surface – piercing hydrofoil.

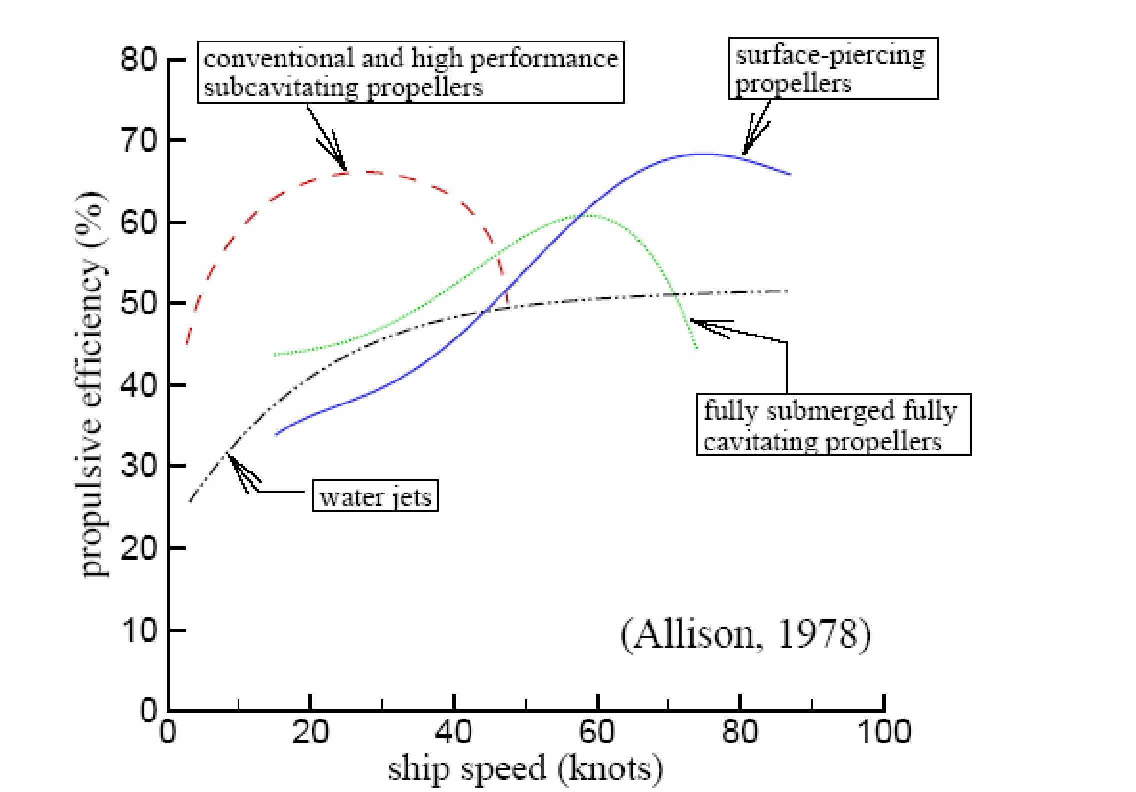

Figure 9. Approximate Max installed efficiency envelopes for different propellers. Taken from [Allison 1978]

II. SURFACE PIERCING PROPELLERS

A. CONVENTIONAL PROPELLER

1. Flow

a. Vortex-Lattice Methods

A VLM was first applied for the analysis of unsteady, fully wetted propeller flows by [Kerwin and Lee 1978]. It was later extended to treat partial sheet cavitation by [Lee 1979] [Breslin et al. 1982]. The method cannot capture the effect of blade thickness on cavities due to the application of the linearized boundary conditions. [Kerwin et al. 1986] Implemented the leading edge correction introduced by [Kinnas 1985, 1991] to the VLM, and named the propeller code PUF-3A. The method placed vortex and source lattices on the mean camber surface and applied a robust arrangement of singularities and control point spacing to produce accurate results [Kinnas and Fine 1989]. Recently, the method has been re-named MPUF-3A for its added ability to search formidchord cavitation [Griffinet al. 1998] [Kosal 1999] [Lee and Kinnas 2001b]. The latest version of MPUF-3A [Lee et al. 2001] also includes the effect of hub, simplified wake alignment using circumferentially averaged velocities, arbitrary shaft inclination [Kinnas and Pyo 1999], and non-linear thickness-loading coupling [Kinnas 1992]. However, flow details at the blade leading edge and tip cannot be captured accurately due to the breakdown of either the linear cavity theory or the employed leading edge and thickness-loading coupling corrections. In addition, the current version of MPUF- 3A does not include the effect of cavity sources in the thickness-loading coupling to correctly model the effect of cavitation. [Y.L. Young]

b. Boundary Element Method

The potential-based BEM developed by [Kinnas and Fine 1990, 1993] was extended to predict mixed cavitation patterns on the back of propeller blades subjected to non-axisymmetric inflows [Fine 1992; Kinnas and Fine 1992; Fine and Kinnas 1993]. The time-dependent cavities were assumed to detach at the blade leading edge, and a wake alignment similar to that of MPUF-3A [Greeley and Kerwin 1982] was applied. The method, named PROPCAV, places constant strength panels on the actual blade and hub surfaces. Thus, PROPCAV inherently includes the effect of nonlinear thickness-

loading coupling and provides a more realistic hub model thanMPUF-3A 3. Similar BEMs were also developed by [Kim and Lee 1996; Caponnetto and Brizzolara 1995]. Recently, [Mueller and Kinnas 1997; Mueller 1998; Mueller and Kinnas 1999] further extended PROPCAV to predict midchord cavitation on either the back or the face of propeller blades. [Young Y.L.]

2. Face and Back Cavitation

Most conventional propellers, the dominant type of cavitation is leading edge back cavitation. Leading edge back cavitation is the cavity that forms on the suction side of the blade and detaches from the leading edge. However, midchord cavitation is the cavity that detaches aft of the leading edge and is becoming more and more common in recent designs. But it is often due to the designer's attempt to increase efficiency by decreasing cavity thickness [Vorus and Mitchell 1994] or designing sections with nearly constant pressure distribution on the suction [Jessup et al. 1994]. Midchord cavitation is also possible on conventional propellers when operating at off design conditions.

PROPCAV has been extended to search for cavity detachments on the back or the face of the blade by [Mueller and Kinnas 1997; Mueller 1998; Mueller and Kinnas 1999]. The search for cavitation on the face (pressure side) of the blade is also necessary because it is common for propellers subjected to off design conditions or non-uniform inflows. Propellers are often designed to produce a certain mean thrust. However, part or the entire blade may experience smaller loadings at certain angular positions due to the non-axisymmetric inflow. As a result, very small or negative angle of attack may occur, which in turn leads to face cavitation. However, the search for face or back cavitation alone may not be sufficient because these two phenomena can alternate or occur simultaneously in a propeller revolution. Alternating or simultaneous face and back cavitation is also very common for controllable pitch propellers. In addition, some of the latest hydrofoil and propeller design intentionally produce simultaneous face and back cavitation to achieve maximum efficiency. Thus, one of the objectives in the modeling of fully submerged propellers is to extend PROPCAV to predict face and/or back cavitation with search cavity detachment on both sides of the blade section. (Fig 12) [Young Y.L.]

B. SUPERCAVITATING PROPELLERS

After reading and annualizing the experimental evidence from Young's paper it shows that the separated zone behind the thick blade trailing edge forms a closed cavity that separates from the practically ideal irrigational flow around a supercavitating blade section [Russel 1958]. Furthermore, the pressure within the separated zone (also called the base pressure) can be assumed to be uniform [Riabouchinsky 1926; Tulin 1953]. However, in high Reynolds number flows, the mean base pressure depends on the mechanics of the wake turbulence [Roshko 1955]. This implies that a turbulent dissipation model, such as the one used in [Vorus and Chen 1987], is necessary to determine the mean base pressure and the extent of the separated zone. These models in the prediction of unsteady 3-D cavitating propeller flows are not practical or capable for the engineering purposes.

To simplify the physics, [Kudo and Ukon 1994] assumed the supercavitating blade section to be base ventilated (i.e. the mean base pressure equal to the vapor pressure), and solved the steady cavitating propeller problem using a 3-D vortexlattice lifting surface method. Later, [Kudo and Kinnas 1995] modified the method to allow for a variable length separated zone model which determines the mean base pressure. However, the length of the separated zone is arbitrarily specified by the user, and has found to affect the pressure and cavity length near the blade trailing edge under fully wetted and partially cavitating conditions. Furthermore, the method of [Kudo and Kinnas 1995] cannot be applied in unsteady cavitating analysis since the length of the separated zone changes with blade angle. In the present method, the assumption of [Kudo and Ukon 1994] is used for the analysis of supercavitating propellers subjected to steady and unsteady inflow. The base pressure is assumed to be constant and equal to the vapor pressure, and the extent of the separated zone at each time step is determined iteratively like a cavity problem. The logic behind this assumption are: [Young Y.L.]

1. The base pressure should equal to the vapor pressure in the case of supercavitation.

2. The separated zone has to communicate with the supercavity in the span-wise direction in the case of mixed cavitation (i.e. one part of the blade is wetted or partially cavitating while another part is supercavitating).

3. Most supercavitating propellers operate in supercavitating conditions.

Hence, the present method solves for the separated zone like an additional cavitation bubble. However, the "openness" at the blade trailing edge poses a problem for the panel method. Thus, a small closing zone, shown in Fig. 10, is introduced. The precise geometry of the closing zone is not important, as long as it is inside the separated region and its trailing edge lies on the aligned wake sheet. As depicted in Fig. 10, this scheme is applicable to fully wetted, partially cavitating, and supercavitating conditions in steady and unsteady flows. In addition, the numerical algorithm for the treatment of supercavitating propellers is the same as that for conventional cavitating propellers with a few modifications to the numerical algorithm. (Fig 11) [Young Y.L.]

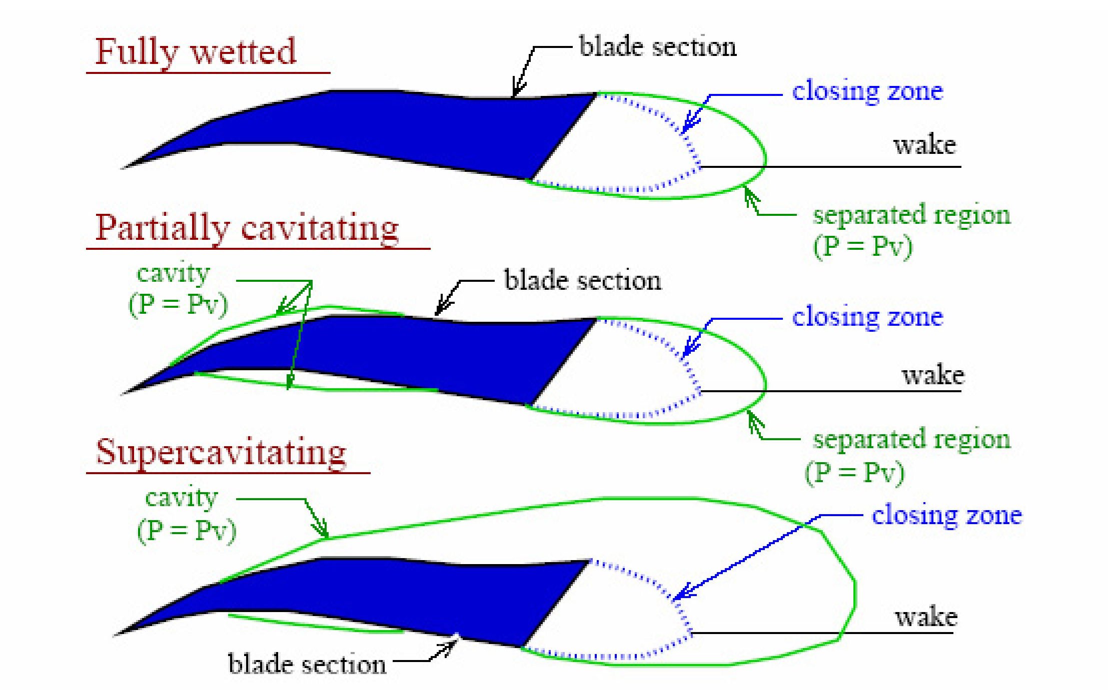

Figure 10. Treatment of Supercavitating blade sections [Young Y.L.]

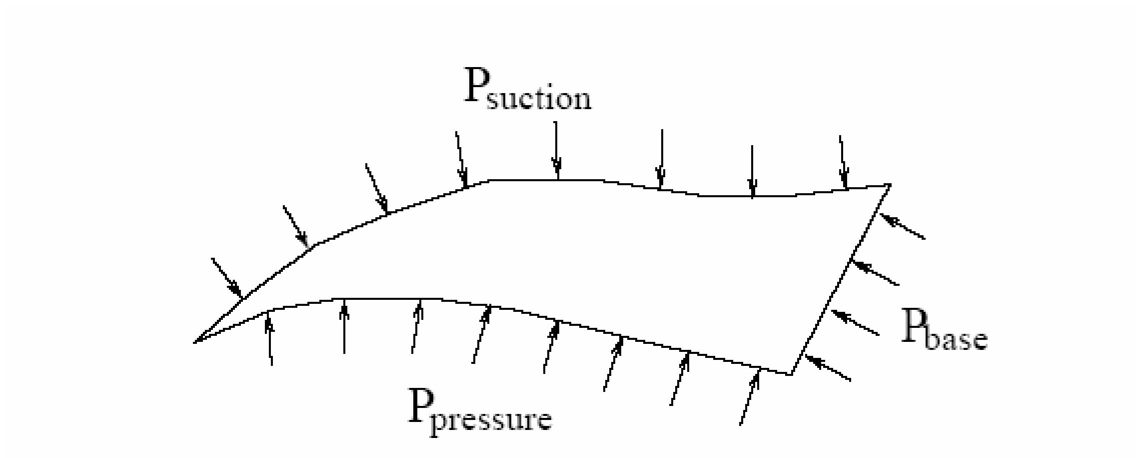

Figure 11. Pressure integration over a blade section with non-zero trailing edge thickness

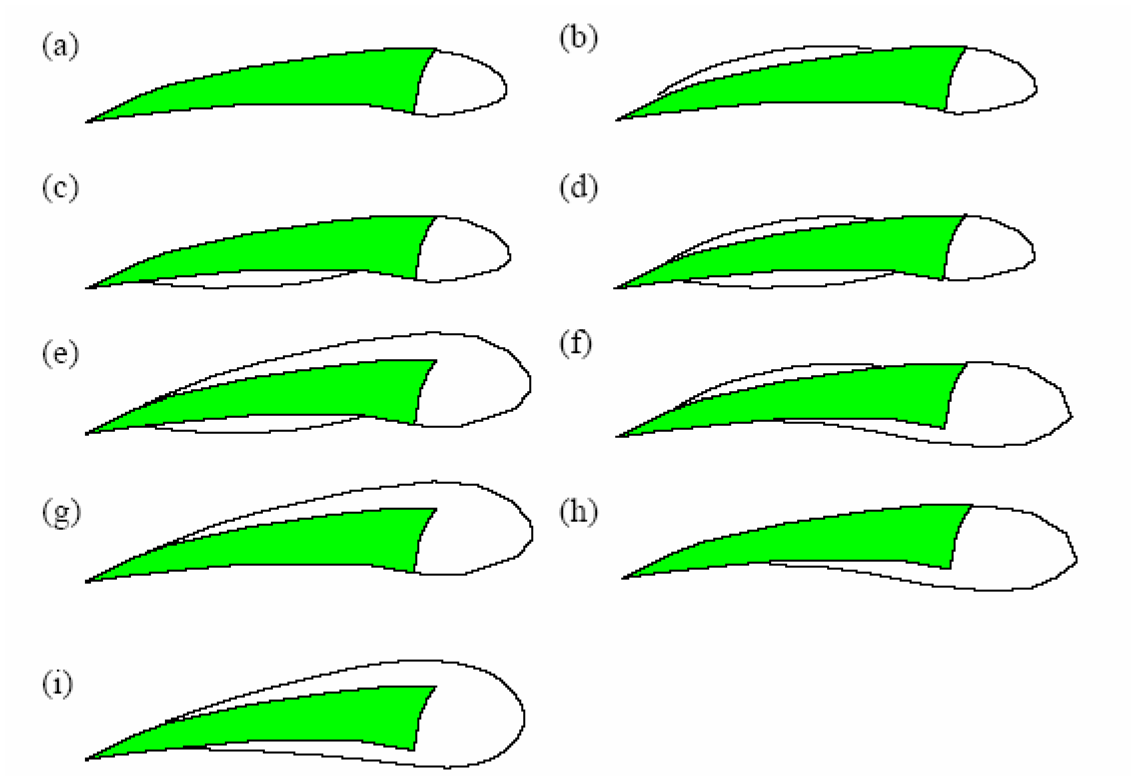

Figure 12. Cavitation patterns on supercavitating propellers that can be predicted by the present method

C. PARTIALLY SUBMERED PROPELLERS

This section determines the performance characteristics of partially submerged propellers. The design of partially submerged propellers was often based on experience, due to the lack of systematic series data and the lack of reliable theoretical design methods. One of the first known experimental studies of partially submerged propellers was presented in [Reynolds 1874], where the effect of immersion on skewed propellers was studied. Many more experimental investigations have been published and the investigation include [Shiba 1953; Hadler and Hecker 1968; Hecker 1973; Rains 1981; Rose and Kruppa 1991; Kruppa 1992; Rose et al. 1993; Wang 1995]. The focus of all these studies was to determine thrust, torque, bending moment, and transverse forces. The influence of blade tip immersion, number of blades, blade pitch, rake, skew, section geometry, as well as shaft yaw and inclination angles was studied. This thesis focuses on defining the shaft yaw angle and the changes it makes to the other parameters of the propeller. More recently, [Olofsson 1996; Miller and Szantyr 1998; Dyson 2000; Dyson et al. 2000] also conducted experiments to determine the dynamic performance of partially submerged propellers with great performance increase and information. The common objective was to study the time dependent hydrodynamic load, and the stresses induced on the propeller blades, shaft, and the hull structure in a defined environment and laboratory.

However as many papers have all stated, model tests are extremely expensive, difficult, and time consuming to perform and give a consistent out put of usable data. The test must be carried out in a variable pressure free-surface tunnel that permits high-speed operations in a set environment. The free surface must be clearly defined [Kruppa 1992] and consistent with other engineering designers and scientist. A multi-component dynamometer is needed to measure primary and secondary forces on the propeller. Experimental studies indicated that the transverse hydrodynamic forces are high in both directions, which can significantly influence vessel performance and shaft stresses [Rose et al. 1993]. Specialized equipment are also needed to simultaneously provide realistic conditions for cavitation inception while maintaining constant water density [Olofsson 1996]. Furthermore, special considerations are needed to address scale issues so that the performance of the model scale, including blade vibration characteristics, resembles that

of the prototype [Olofsson 1996; Dyson 2000]. Thus, the development of reliable, versatile, and robust computational tools to predict propeller performance is crucial to the design and application of partially submerged propellers in various applications.

1. Numerical Method

a. Lifting Line Methods

The first effort to model partially submerged propeller was carried out by [Oberembt 1968]. He used a lifting line approach to calculate the characteristics of partially submerged propellers. [Oberembt 1968] assumed that the propeller is lightly loaded such that no natural ventilation of the propeller and its vortex wake occur. However, this is often not the case for partially submerged propellers. A lifting-line approach which includes the effect of propeller ventilation was developed by Furuya in [Furuya 1984, 1985]. He used linearized boundary conditions and applied the image method to account for free surface effects. He also assumed the face portion of the blades to be fully wetted and the back portion of the blades to be fully ventilated starting from the blade leading edge. The blades were reduced to a series of lifting lines, and method was combined with a 2-D water entry-and-exit theory developed by [Wang 1977, 1979] to determine thrust and torque coefficients. Furuya compared the predicted mean thrust and torque coefficients with experimental measurements obtained by [Hadler and Hecker 1968]. In general, the predicted thrust coefficients were within acceptable range compared to measured values. However, there were significant discrepancies with torque coefficients. Furuya attributed the discrepancies to the effects of nonlinearity, absence of the blade and cavity thickness representation in the induced velocity calculation, and uncertainties in interpreting the experimental data. He also stated that the application of lifting-line theory is limited due to the relative large induced velocities at low advance coefficients. [Young Y.L.]

b. Lifting Surface Methods

An unsteady lifting surface method was employed by [Wang et al. 1990b] for the analysis of 3-D fully ventilated thin foils entering into initially calm water. The method was later extended by [Wang et al. 1990a] and [Wang et al. 1992] to predict the

performance of fully ventilated partially submerged propellers with its shaft above the water surface. Similar to [Furuya 1984, 1985], the method assumed the flow to separate from both the leading edge and trailing edge of the the blade, forming on the suction side a cavity that vents to the atmosphere. Discrete line vortices and sources were placed on the face portion of the blade to simulate the effect of blade loading and cavity thickness, respectively. Line sources were also placed on the cavity surface behind the trailing edge of the blade to represent the cavity thickness in the wake. A helical surface with constant radius and pitch were used to construct the trailing vortex sheets. The negative image method was used to account for the effect of the free surface. The effect of the blade thickness was neglected in the computation. Comparisons were presented with both experimental measurements by [Hadler and Hecker 1968] and numerical predictions by [Furuya 1984, 1985]. The predictions were within reasonable agreement with experimental values for propeller MAU4-60 for a limited data range. However, substantial discrepancies were observed for propeller 4002 with both experimental values and numerical predictions by [Furuya 1984, 1985]. [Young Y.L.]

The 3-D lifting surface VLM developed by [Kudo and Ukon 1994] and [Kudo and Kinnas 1995] for the analysis of supercavitating propellers has also been extended for the analysis of surface-piercing propellers in there program. The VLM performs all the calculations assuming the propeller is fully submerged, and then multiplies the resulting forces with the propeller submergence ratio. This program was used in Yin Lu Young paper. As a result, only the mean forces can be predicted while the complicated phenomena of blade's entry to, and exit from, the water surface are completely ignored.

c. Boundary Element Methods

A 2-D time-marching BEM was developed by [Savineau and Kinnas 1995] for the analysis of the flow field around a fully ventilated partially submerged hydrofoil. However, this method only accounts for the hydrofoil's entry to, but not exit from, the water surface. At a zero yaw propeller angle. The negative image method was used so the effects of water jets and change in free surface elevation were ignored and not looked at. [Young Y.L.]

2. Green's Formula

Since the propeller is partially submerged, the computational boundary must also include the free surface. Hence, the perturbation potential, p, at every point p on the combined wetted blade surface SWB(t), ventilated cavity surface SC1(t) [SC2(t) [SC3(t), and free surface SF (t), must satisfy Green's third identity:

$$2\pi\phi_p(t) = \int\int_{S(t)} \left[\phi_q(t)\frac{\partial G(p;q)}{\partial n_q(t)} - G(p;q)\frac{\partial \phi_q(t)}{\partial n_q(t)}\right] dS$$

where S(t) _ SWB(t)[SC1(t)[SC2(t)[SC3(t)[SF (t) is the combined surfaced as defined in the blade section example shown on Fig. 13. is the unit vector normal to the integration surface, with the positive direction pointing into the fluid domain. [Young Y.L.]

As in the case of fully submerged propellers, the "exact" ventilated cavity surfaces, SC1(t) [SC2(t) [SC3(t), are unknown and have to be determined as part of the solution. Thus, the ventilated cavity surfaces are approximated with the blade surface underneath the cavity, SC2(t) ! SCB(t), and the portion of the wake surface which is overlapped by the cavity, SC1(t) [SC3(t) ! SCW(t). The definition of SCB(t) and SCW(t) are shown in Fig. 13. [Young Y.L.]

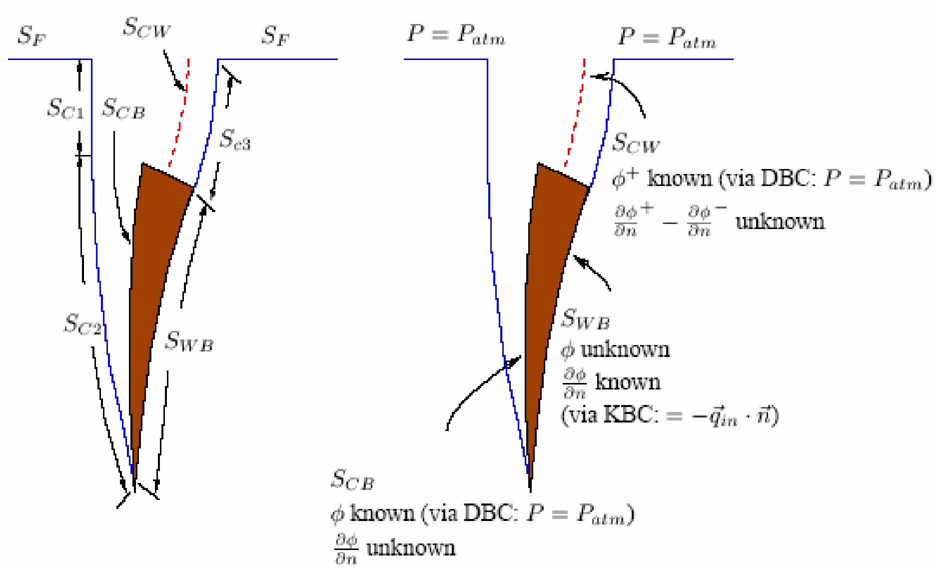

Figure 13. Definition of "exact" and approximated flow boundaries

D. VENTILATED CAVITY DETACHMENT SEARCH CRITERION

Depending on the flow conditions and the blade section geometry, the ventilated cavities may detach aft of the blade leading edge. The cavity detachment location on the suction side of the blade are searched for in an iterative manner at teach time step until the smooth detachment condition is satisfied. In addition, due to the interruption of the free surface, the following detachment conditions must also be satisfied for partially submerged propellers: (Fig 14) [Young Y.L.]

a. The ventilated cavities must detach at or prior to the blade trailing edge and

b. During the exit phase (i.e. when part of the blade is departing the free surface), the ventilated cavities must detach at or aft of the intersection between the blade section and the free surface.

A schematic diagram showing different cavity detachment locations for a surface-piercing blade section is depicted in Fig. 14. It should be noted that the ventilated cavities on the pressure side of the blade are always assumed to detach from the blade trailing edge. It is possible to also search for cavity detachment locations on the pressure side. However, such occurrence is unlikely due to the high-speed operation of partially submerged propellers. [Young Y.L.]

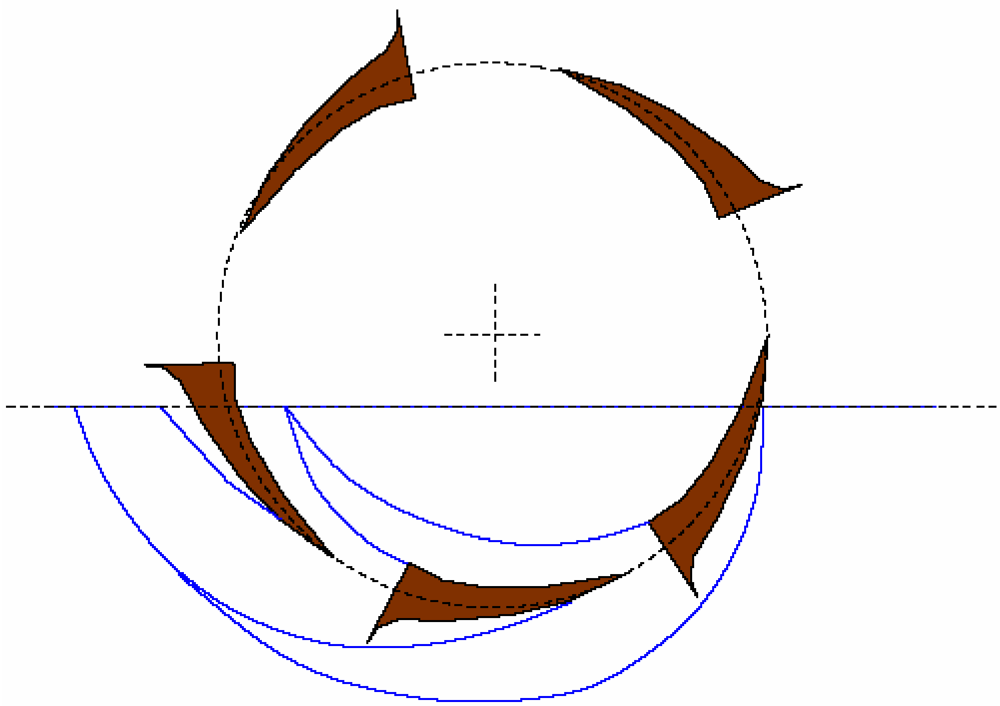

Figure 14. Graphic illustration of ventilated cavity patterns that satisfy the cavity detachment condition on a partially submerged blade section. In addition, the cavities are assumed to vent to the atmosphere. [Young Y.L.]

E. SURFACE-PIERCING

In order to quantify the added hydrodynamic forces associated with jet sprays generated at the blade entry and exit phase, a systematic 2-D study has been initiated in this thesis. The exact nonlinear free surface boundary conditions are used and the effect of Froude number will be studied. The predicted forces on the wetted part of the hydrofoil will be compared to those obtained using the negative image method. The planned progression of the 2-D study (Fig. 15): [Young Y.L.]

1. Vertical water entry of a symmetric wedge.

2. Oblique water entry of a surface-piercing hydrofoil.

3. Vertical water exit of a symmetric wedge.

4. Oblique water exit of a surface-piercing hydrofoil.

5. Water entry and exit of a surface-piercing hydrofoil.

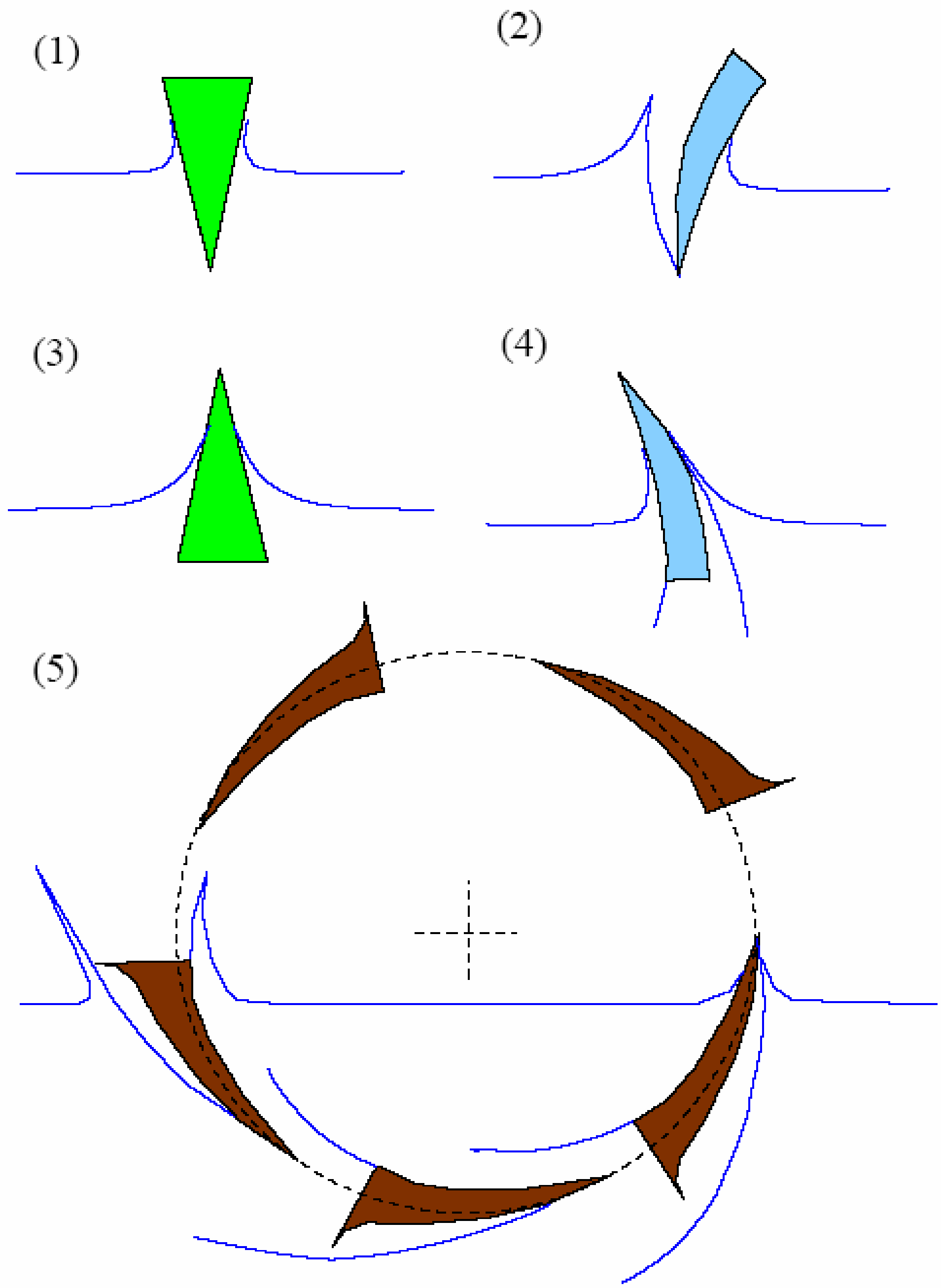

Figure 15. Planned progression of the 2-D nonlinear study for the water entry and exit problem of a surface-piercing hydrofoil.

1. Previous Work

The problem of a 2-D rigid wedge entering the water was first studied by[Von Karman 1929] and [Wagner 1932]. They assumed that the velocity field around the wetted part of the body can be approximated with the flow field around an infinitely long flat plate. Von Karman [Von Karman 1929] assumed that the free surface is flat, while Wagner [Wagner 1932] accounted for the deformation of the free surface. The similarity method of Wagner [Wagner 1932] reduced the unsteady problem to a steady one. Since then, the slamming problem on a 2-D body has been extensively studied by [Makie 1969; Cox 1971; Yim 1974]. In particular, [Yim 1974] applied a linearized theory to study the water entry and exit of a thin foil and a symmetric wedge with ventilation. All of these studies were done at a zero degree yaw angle. But Later, [Wang 1977, 1979] also applied linear theory to study the vertical and oblique entry of a fully ventilated foil into a horizontal layer of water with arbitrary thickness. This raised the method of [Wang 1977, 1979] and later extended by [Furuya 1984, 1985] for the performance prediction of surface-piercing propellers in a new study and environment.

2. Formulation

The formulation for surface-piercing (also called partially submerged) propellers, are

$$\frac{\partial \phi(x,y,z,t)}{\partial n} = -\vec{U}_{in}(x,y,z,t)\cdot\vec{n} \qquad \delta(x,y,z,t)=0$$

is the same as that for fully submerged propellers with the following exceptions(Young & Kinnas 2001a, Young & Kinnas 2001b):

1. The dynamic boundary condition requires that the pressure everywhere on the free surface , and on the ventilated cavity surface, and to be constant and equal to the atmospheric pressure,
2. The linearized free surface condition is applied:

   $$\frac{\partial^2 \phi}{\partial t^2}(x,y,z,t) + g\frac{\partial \phi}{\partial y_s}(x,y,z,t) = 0 \qquad \text{at} \quad y_s = -R+h$$

   where ys are h

are the vertical ship-fixed coordinate and the blade tip immersion is defined. Respectively R= D/2 is the blade radius.

3. The assumption of infinite Froude number is applied, which reduces the top Eqn. $\phi(x, y, z, t) = 0 \quad \text{at} \quad y_s = -R + h$ this implies that the "negative" image method can be used to account for the effect of the free surface. The assumption that the Froude number grows without bounds is valid because surface-piercing propellers usually operate at very high speeds. (Shiba 1953) and (Yim 1974) have also concluded that gravity effects are negligible for Froude numbers greater than 3.

4. The source and dipole strengths on the "dry" part of the blades are set equal to zero. Thus, the number of unknowns is reduced to the number of fully submerged panels.

5. In order to save computer time, only one iteration is performed at each time step (i.e. the method does not iterate to determine the exact thickness of the ventilated cavity). This is assumed to be a valid approximation since the pressure is set equal to atmospheric on the ventilated portion of the blades, and the pressures on the wetted portion of the blades are not expected to be significantly affected by small differences in cavity height.

It should be noted that the method is still in the development stage for the analysis of partially submerged propellers. Thus, the effect of partially submerged panels is currently ignored. [Kinnas S.A. 2002]

III. CONCLUSIONS

A. CONCLUSIONS

After months of research there is very little written documentation on for an age old propulsion design problem. This thesis addressed multiple methods to predict the performance of supercavitating and surface-piercing propellers. In the past, the only way to be able to predict the performance was by full scale modeling or estimations based on experience. The method I am most familiar with. Using the full scale method I have proven a 3% to 5% improvement in the efficiency (thrust) of surface piercing propellers, with respect to the angle of the propeller shaft and position. This thesis addresses the preliminary calculations based on the basic pitch/diameter geometry suggest that about 3-5% efficiency is lost if the shaft is parallel to the flow, compared to skewed a few degrees in the "paddlewheel" direction at certain speeds. More accurate calculations based on the lift characteristics of each blade, on the angle of attack and the flow of water over each blade and given a set of basic assumption on the over all performance of each blade, as the blade enters and leaves the water; are used to determine the increase in efficiency.

B. FULL SCALE MODEL TESTING

While working at a Propeller Shop in Florida numerous full scale design and modifications were made successful through trial and error calculations. The research for this thesis started back 15 years ago on the Indian River in Cocoa, Fl. Working at a local propeller refurbishing shop I learned how to build and modify numerous propellers configurations for various hull designs. These Calculations were all based on trial and error data compiled over numerous years of hands on research and development. The different propeller designs and blade modifications were used to provide greater thrust or optimum speed and performance. Often different and unique hull forms needed different and unique propellers. Realizing the shape and size of the blade performed differently helping me to understand the basic fundamentals for basic propeller and surface piercing design. The learning processes was make changes to the propeller and test the propeller until you acquire the proper end result or performance, by the trial and error process. After modifying hundreds of propellers, I started to learn how each little change made a

difference in performance. One of the biggest performance gain or modification was the location and the angle of the propeller during operation.

A blade fixture (Fig. 19) consists of a machinist's micrometer to measure the depth, along a detented arm swung in a plane, having 5 degree increments pin locator positions. This device provided the mechanism to describe the propeller blades in a radial format the resulting plot in 2-D is in (Table 1) using a 14x19 Propeller Blade. This propeller was used to document the blade shape and size. This Radial Coordinate System is used in most airfoil propeller analysis. Another Coordinate system used in the NASA Material Science Lab at Kennedy Space Center, Florida (figure 20) is the Brown and Sharp measurement equipment. This data provides a X, Y, & Z coordinate system description of the blade shape. (Table 6) This data was best used in CFD ACE GOM. (Fig 23) The measurements from Ace Geo were made to two existing types of propellers. This dimensional analysis is a necessary step to interface known propeller designs with Computational Analysis tools. Knowing the surface contour, a computer can predict the water flow across a propeller. The evaluated propeller designs are: A fully immersed design propeller, the "14X 19" (Fig 19) results are in (Table1) for a recreational vessel and two Surface Piercing propeller designs; A Masco RE (table 2) and Cleaver propellers (table 3), and (Fig 16) Surface Piercing Propeller (Chopper).

C. FACE AND BACK CAVITATION

The detail description of Face and Back Cavitation in Yin Lu Young paper is second to none. She states that alternating face and back cavitation are becoming more and more common in recent propeller designs, but I was unable to find experimental results proving or validating the method. Systematic comparisons should be made between the predicted and measured cavitation patterns and blade forces. Additional studies are also needed to test the sensitivity of method to different space and time discretizations for a wide range of propeller geometries and operating conditions. In the case of unsteady face and back cavitation, the following concerns she addresses should also be addressed: [Young Y, L]

1. The hydro elastic response of the propeller, particularly in the case of alternating face and back cavitation.

2. A more comprehensive wake model, such as the one presented in [Lee 2002], should be incorporated to the current method. At this time, the wake is aligned with the circumferentially averaged inflow. However, most propellers that exhibit face and back cavitation patterns are subjected to inclined inflow. In that case, the time-invariant wake model may be an oversimplification.

D. SUPERCAVITATING PROPELLERS

For supercavitating propellers, the current method assumes the pressure to be constant and equal to the vapor pressure on the separated region behind non-zero thickness blade trailing edge sections. Based on this assumption, the method is able to predict the extent and thickness of the separated region in steady and unsteady flow conditions. However, additional studies are needed to determine the effect of prescribed separated region pressure on the predicted blade forces in the case of fully wetted and partially cavitating flow. Under the current algorithm, it is actually possible to prescribe a different pressure, such as that measured in experiment or computed using viscous flow analysis, on the separated region. A more careful study is also needed to predict how the pressure changes along the trailing edge when one part of the blade is wetted or partially cavitating, and another is supercavitating. Additional validation and convergence are also needed before this method can be reliably use for the design and analysis of supercavitating propellers. The two concerns previous listed for the prediction of face and back cavitation should also be addressed for supercavitating propellers.

E. SURFACE-PIERCING PROPELLERS

Although the current performance prediction of surface piercing propellers are in reasonable agreement with experiments, considerable research are required before the method can be reliably use in the design and analysis of surface-piercing propellers:

The Modeling of partially submerged panels can be accomplished by using a method similar to the split-panel technique used in Professor Kinnas's and UT's propeller program PROP CAV.

Modeling of the jet sprays. Complete the current 2-D nonlinear study of surface-piercing hydrofoils, and find a simplified approach to incorporate the results into the 3-D model. A possible algorithm is provided below by some of the University of Texas Engineering program and Prof. S, Kinnas:

a. Solve the 3-D problem using the negative image method.

b. Apply the 2-D algorithm to each radial blade section, assuming the incident angle is determined by the sectional geometry and global flow velocities (i.e. inflow velocity and propeller induced velocities).

c. Perform the same 2-D calculation using the negative image method.

d. Calculate the difference between the 2-D fully nonlinear solutions from that obtained using the 2-D negative image method. Apply the calculated corrections to the sectional lift and drag coefficients in the 3-D model using the assumed incidence angles. This can be a fast, but reasonable, approach for the design of surface-piercing propellers.

3. Modeling of the blade vibration via hydro elastic coupling. A possible algorithm is provided below:

a. Perform the hydrodynamic analysis (using the current 3-D BEM) assuming the blade the rigid.

b. Perform the structural analysis (using a 3-D finite element method) with the unsteady pressures obtained from (1) as input.

c. Perform the hydrodynamic analysis using the deformed blade geometry. Note that the distortion on each blade may be different. In addition, the blade deformation at each blade angle may also be different. Furthermore, the effect of the unsteady blade motion should also be included in the hydrodynamic analysis. This effect can be approximated by modifying the kinematics boundary conditions the vertical coordinate of the mean-camber line with respect to the nose tail line.

d. Perform the structural analysis based on the new blade geometry and pressure distributions.

4. Coupling the method with an unsteady Euler solver to obtain a more realistic effective wake velocity.

5. Include a more realistic wake alignment model, especially for cases with nonzero shaft yaw and inclination angle.

F. DISCUSSION AND CALCULATION

The Measurements obtained by the propeller measuring device (Fig. 19) were plotted in (Table 1 & 7) as a Radius vs. depth. Knowing that the propeller has a circular flow over the blade at a fixed radius from the hub's centerline, the ability to change the blade angle of attack when the propeller is in motion is dependant on the yaw angle. If the yaw angle changes it will produce a circumference to radial flow path change then the blade root circumference flow path can be evaluated to a arbitrary radial flow path (Table 4). A comparison of this flow path (Table 5) indicates a pitch increase. This will increase the total flow and lift vector (2-D) across the propeller blades resulting in an increase in thrust. There for a thrust increase will be produced by a yaw angle increase.

In 1988 Pal Kamen a former employee of Arneson, outdrive INC. suggested that about 3-5% efficiency is lost if the shaft is parallel to the flow, compared to skewed few degrees in the "paddlewheel" direction. Note, that even the 1860-something original patent for a surface-piercing propeller shows a skewed shaft!

Also note that shafts inclined downward in the vertical plane, behind a high-dead rise V hull, intersect the extruded water plane at a skew angle. This is the best explanation for why inboard-turning propellers are more efficient than outboard-turning (although they don't maneuver as well at low speeds).

As for basic formulas, if you know the thrust and torque coefficient of the propeller you can back out a lift/drag ratio or "drag angle" of the blades and from there estimate the effect of shaft skew by integrating these forces around the immersed half-circle.

With help provided by Prof. Spyros A. Kinnas and Hanseong Lee from the University of Texas we got results from their computer program PropCav. As expected the program predicted that the thrust (force along ship direction), increases in the case of

change in the shaft angle. Most of thrust increase with inclined shaft was due to the side force since the side force (Z-direction force) was about the same order of x-direction force. There was also an increase in efficiency.

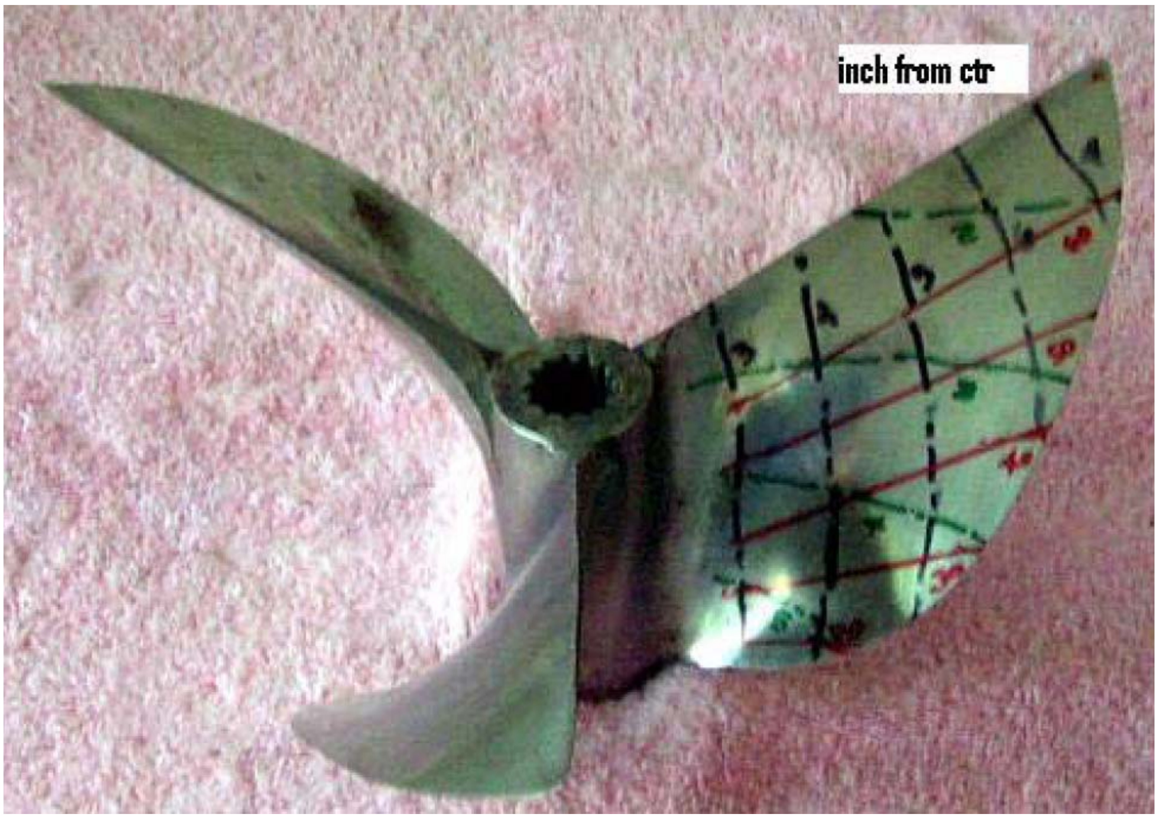

Figure 16. Surface Piercing Propeller.(Chopper)

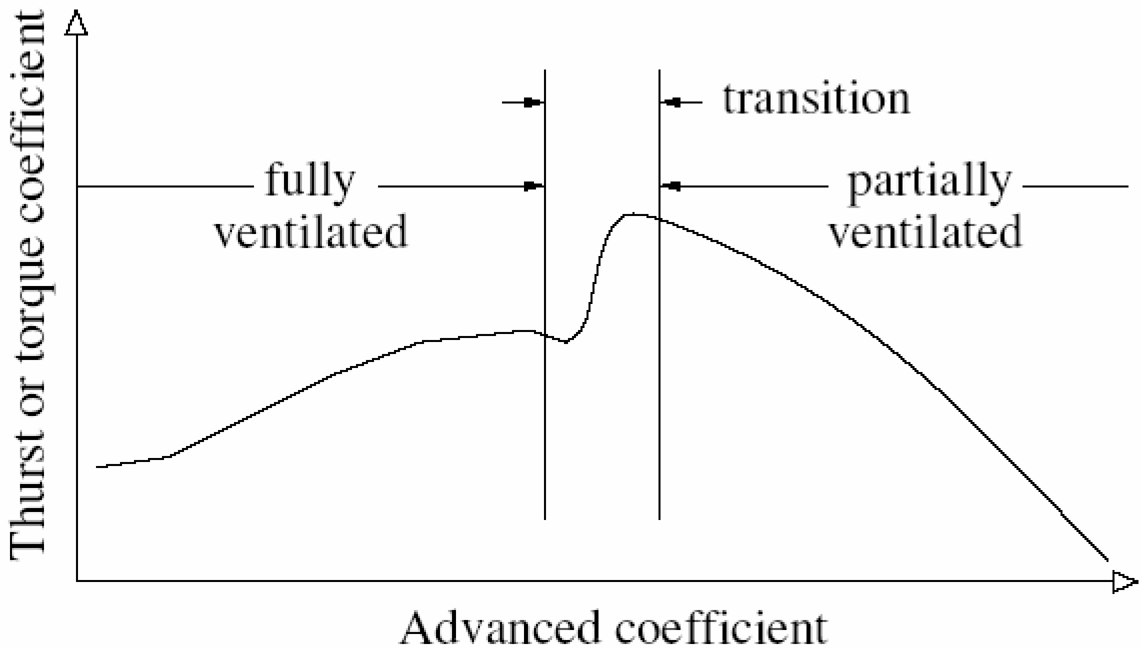

Figure 2: Schematic diagram of the three major flow regimes. Shown in (Young & Kinnas 2003c).

Figure 17. Schematic diagram

CHARACTERISTICS OF AIRFOIL SECTIONS FROM TESTS IN VARIABLE-DENSITY WIND TUNNEL 303

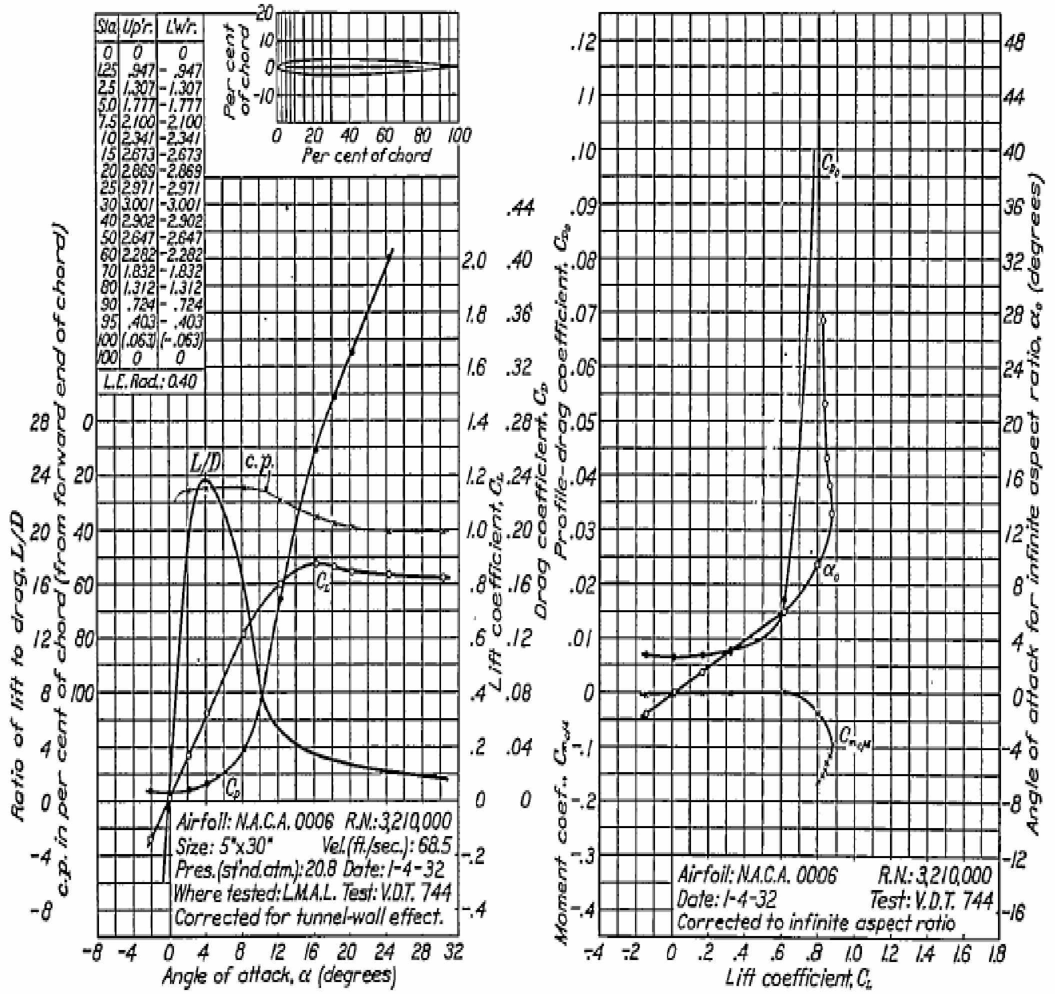

FIGURE 4.—N.A.C.A. 0006 airfoil.

Figure 18. Characteristics of Airfoil section 2-D

Figure 19. Propeller measuring device

Figure 20. Propeller measuring device Kennedy Space Center

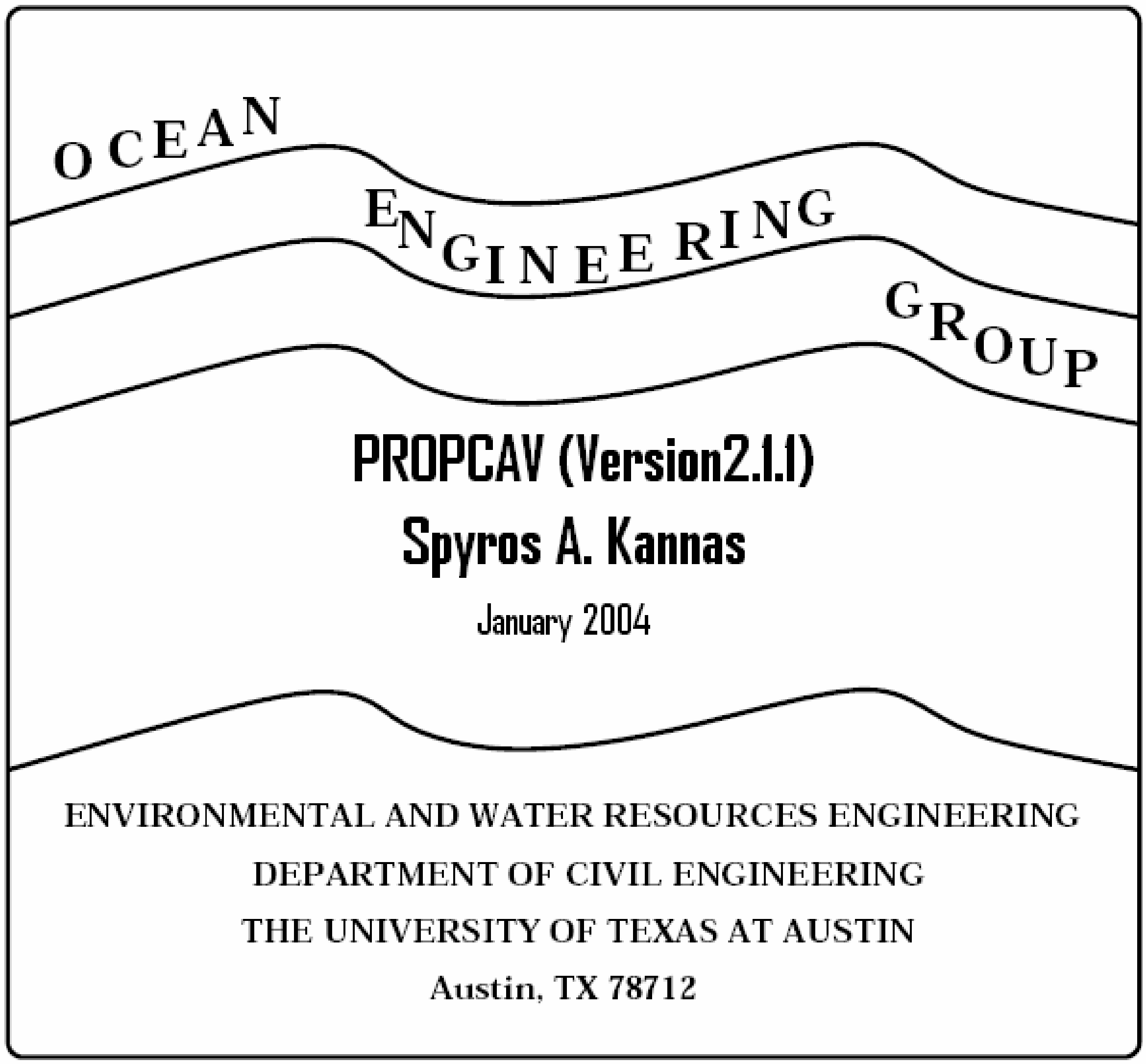

Figure 21. PropCav (Version 2.1.1)

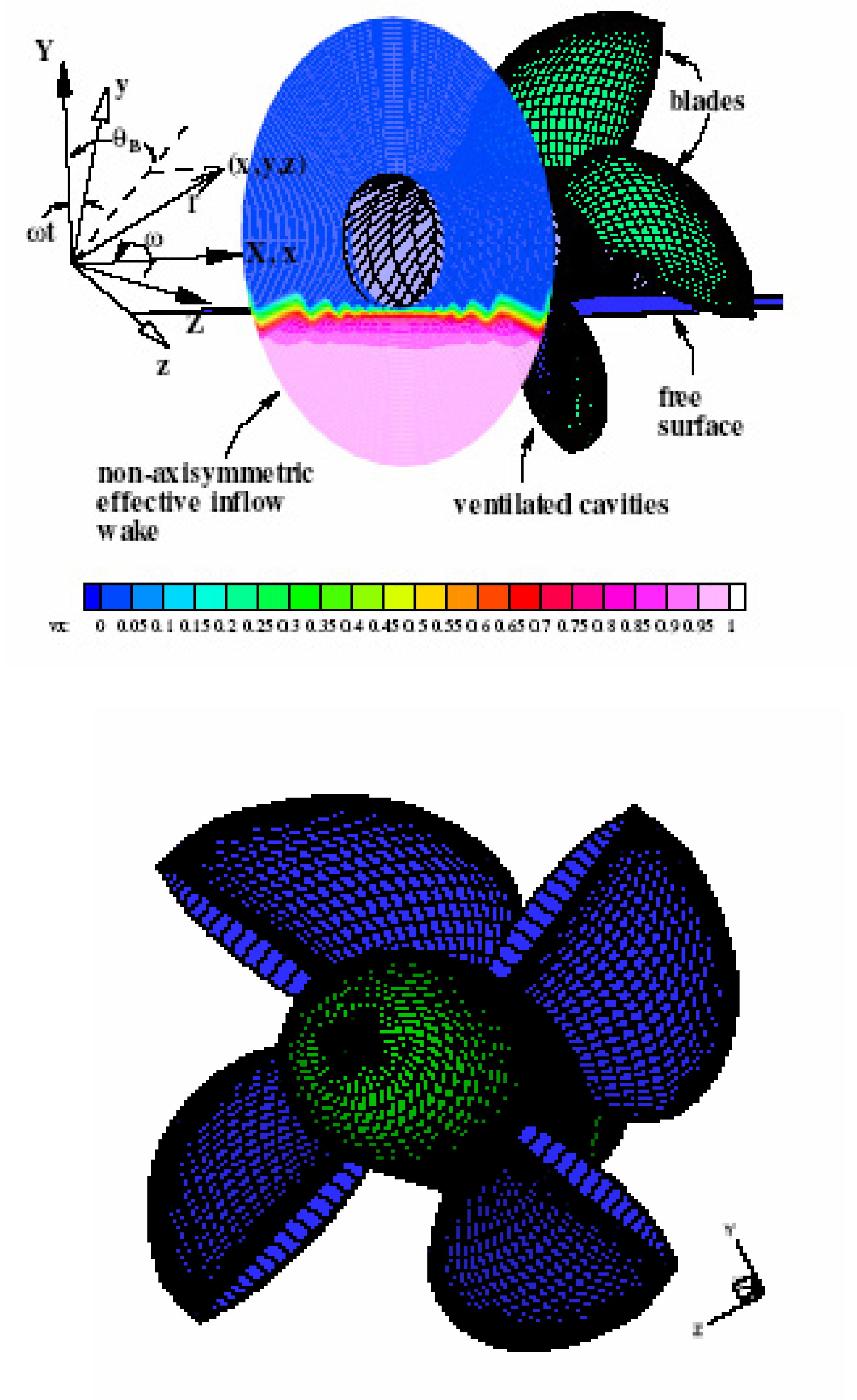

Figure 22. Surface Piercing Propellers

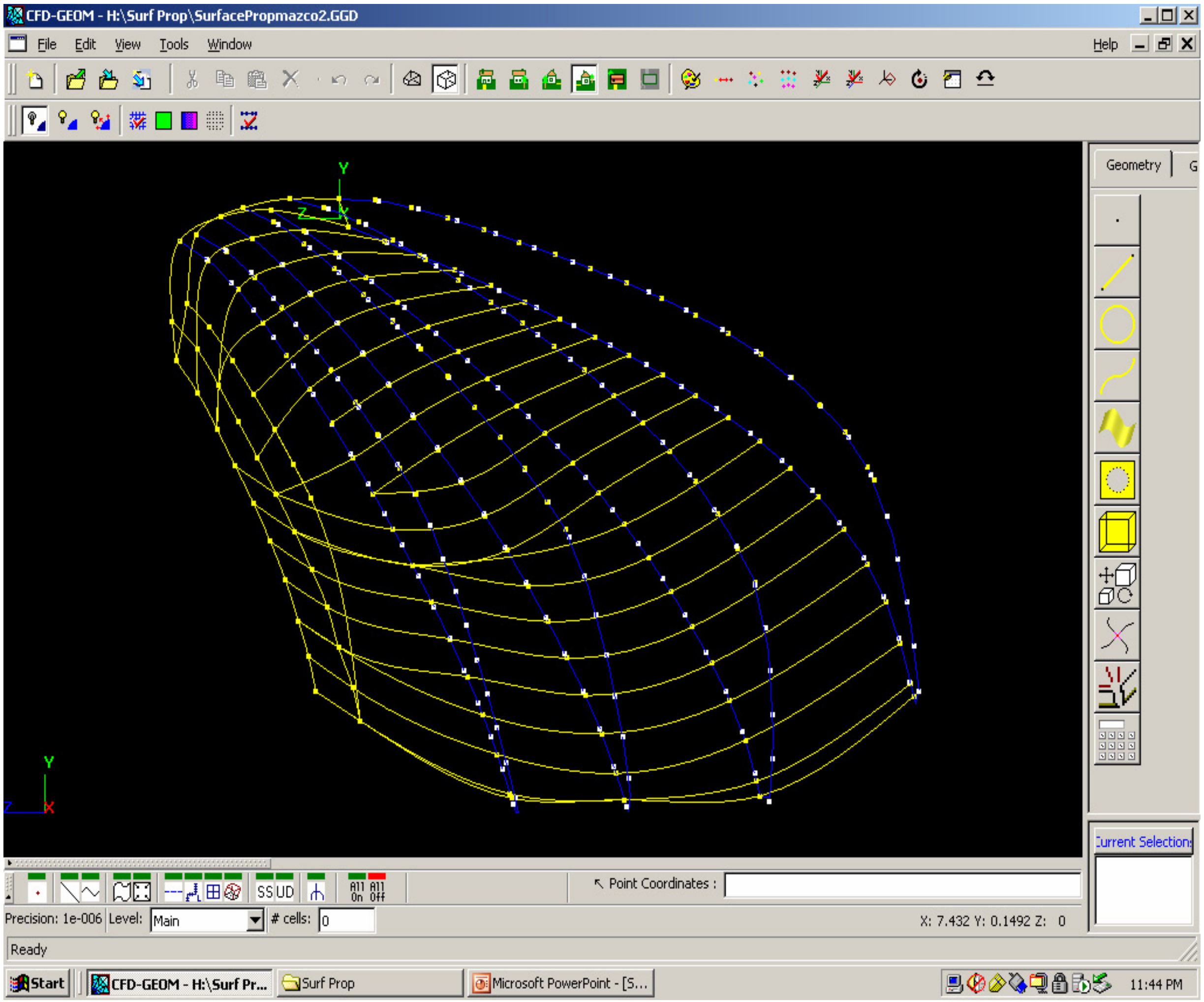

Figure 23. CFD-Geom

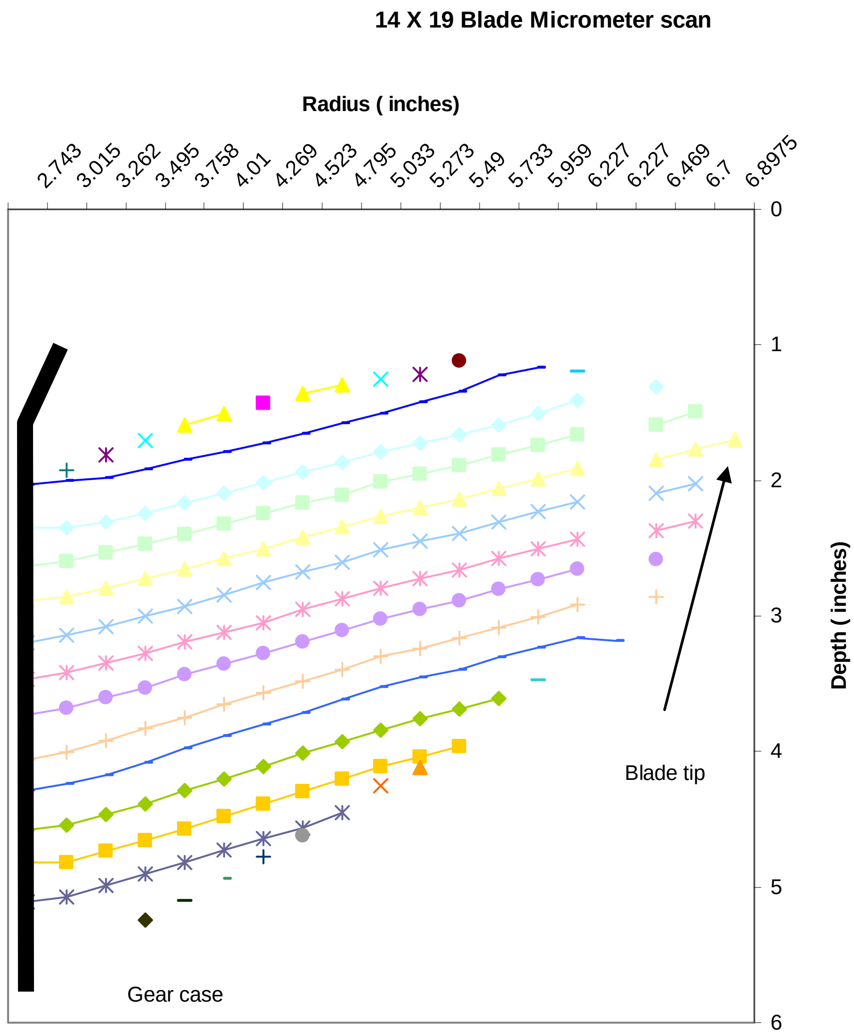

Table 1. 14 x 19 Propeller blade

#	X	Y	Z	#	X	Y	Z
2	1.46	-0.91	-30.86	91	3.63	-0.37	-27.89
3	1.55	-0.97	-30.86	92	3.75	-0.42	-27.89
4	1.63	-1.04	-30.86	93	3.86	-0.48	-27.89
5	1.70	-1.12	-30.86	94	3.97	-0.54	-27.89
6	1.76	-1.20	-30.86	95	4.08	-0.60	-27.89
7	1.82	-1.29	-30.86	96	4.19	-0.66	-27.89
8	1.88	-1.37	-30.86	97	4.30	-0.73	-27.89
9	1.93	-1.46	-30.86	98	4.41	-0.80	-27.89
10	1.98	-1.55	-30.86	99	4.51	-0.87	-27.89
11	2.03	-1.64	-30.86	100	4.61	-0.94	-27.89
12	2.07	-1.72	-30.86	101	4.71	-1.02	-27.89
13	2.12	-1.81	-30.86	102	4.81	-1.09	-27.89
14	2.17	-1.90	-30.86	103	4.91	-1.17	-27.89
15	2.21	-2.00	-30.86	104	5.01	-1.25	-27.89
16	2.22	-2.01	-30.86	105	5.11	-1.33	-27.89
17	1.60	-0.60	-29.93	106	5.20	-1.42	-27.89
18	1.69	-0.64	-29.93	107	5.29	-1.50	-27.89
19	1.78	-0.69	-29.93	108	5.39	-1.59	-27.89
20	1.87	-0.75	-29.93	109	5.47	-1.68	-27.89
21	1.95	-0.81	-29.93	110	5.56	-1.77	-27.89
22	2.03	-0.87	-29.93	111	5.64	-1.87	-27.89
23	2.11	-0.94	-29.93	112	5.72	-1.97	-27.89
24	2.18	-1.01	-29.93	113	5.80	-2.07	-27.89
25	2.25	-1.08	-29.93	114	6.73	-1.36	-26.90
26	2.33	-1.15	-29.93	115	2.05	0.05	-26.89
27	2.40	-1.22	-29.93	116	2.17	0.50	-26.89
28	2.47	-1.29	-29.93	117	2.30	0.51	-26.89
29	2.53	-1.37	-29.93	118	2.42	0.52	-26.89
30	2.60	-1.44	-29.93	119	2.55	0.53	-26.89
31	2.67	-1.52	-29.93	120	2.68	0.54	-26.89
32	2.73	-1.60	-29.93	121	2.80	0.54	-26.89
33	2.80	-1.67	-29.93	122	2.93	0.54	-26.89
34	2.86	-1.75	-29.93	123	3.06	0.54	-26.89
35	2.92	-1.83	-29.93	124	3.18	0.53	-26.89
36	2.99	-1.91	-29.93	125	3.31	0.52	-26.89
37	3.05	-1.99	-29.93	126	3.43	0.51	-26.89
38	3.11	-2.07	-29.93	127	3.56	0.49	-26.89
39	3.16	-2.15	-29.93	128	3.69	0.48	-26.89
40	3.22	-2.24	-29.93	129	3.81	0.45	-26.89
41	3.27	-2.33	-29.93	130	3.93	0.43	-26.89
42	3.32	-2.42	-29.93	131	4.06	0.40	-26.89
43	3.37	-2.51	-29.93	132	4.18	0.37	-26.89
44	4.51	-2.42	-28.95	133	4.30	0.33	-26.89
45	1.66	-0.27	-28.94	134	4.42	0.29	-26.89
46	1.79	-0.29	-28.94	135	4.54	0.25	-26.89

Table 2. Kennedy Space Center 28 pitch Mazco X/Y

47	1.91	-0.33	-28.94	136	4.66	0.21	-26.90
48	2.03	-0.38	-28.94	137	4.78	0.16	-26.90
49	2.15	-0.43	-28.94	138	4.89	0.11	-26.90
50	2.26	-0.49	-28.94	139	5.01	0.05	-26.90
51	2.37	-0.55	-28.94	140	5.12	0.00	-26.90
52	2.49	-0.60	-28.94	141	5.23	-0.06	-26.90
53	2.60	-0.67	-28.94	142	5.34	-0.12	-26.90
54	2.71	-0.73	-28.95	143	5.45	-0.18	-26.90
55	2.81	-0.79	-28.95	144	5.56	-0.25	-26.90
56	2.99	-0.86	-28.95	145	5.67	-0.32	-26.90
57	3.02	-0.93	-28.95	146	5.77	-0.39	-26.90
58	3.13	-1.01	-28.95	147	5.88	-0.46	-26.90
59	3.23	-1.08	-28.95	148	5.98	-0.53	-26.90
60	3.33	-1.16	-28.95	149	6.08	-0.60	-26.90
61	3.42	-1.24	-28.95	150	6.18	-0.67	-26.90
62	3.52	-1.33	-28.95	151	6.28	-0.76	-26.90
63	3.61	-1.41	-28.95	152	6.38	-0.84	-26.90
64	3.70	-1.50	-28.95	153	6.47	-0.93	-26.90
65	3.80	-1.58	-28.95	154	6.55	-1.04	-26.90
66	3.89	-1.67	-28.95	155	6.62	-1.15	-26.90
67	3.98	-1.76	-28.95	156	6.68	-1.26	-26.90
68	4.06	-1.85	-28.95	157	7.04	-0.25	-26.11
69	4.15	-1.94	-28.95	158	4.26	1.00	-26.10
70	4.23	-2.04	-28.93	159	4.39	0.99	-26.10
71	4.31	-2.14	-28.95	160	4.52	0.98	-26.10
72	4.39	-2.24	-28.95	161	4.64	0.97	-26.10
73	4.46	-2.34	-28.95	162	4.77	0.96	-26.10
74	5.85	-2.14	-27.89	163	4.89	0.94	-26.10
75	1.66	0.08	-27.88	164	5.02	0.92	-26.10
76	1.80	0.09	-27.88	165	5.14	0.90	-26.10
77	1.93	0.08	-27.88	166	5.27	0.87	-26.10
78	2.06	0.07	-27.88	167	5.39	0.84	-26.10
79	2.18	0.05	-27.88	168	5.51	0.80	-26.10
80	2.31	0.03	-27.89	169	5.63	0.76	-26.10
81	2.43	0.01	-27.89	170	5.75	0.72	-26.10
82	2.55	-0.02	-27.89	171	5.67	0.67	-26.10
83	2.68	-0.05	-27.89	172	5.98	0.61	-26.10
84	2.80	-0.08	-27.89	173	6.10	0.56	-26.10
85	2.92	-0.11	-27.89	174	6.21	0.50	-26.10
86	3.04	-0.14	-27.89	175	6.32	0.43	-26.11
87	3.16	-0.18	-27.89	176	6.42	0.36	-26.11
88	3.28	-0.22	-27.89	177	6.53	0.29	-26.11
89	3.40	-0.27	-27.89				
90	3.52	-0.32	-27.89				

Table 2. Kennedy Space Center 28 pitch Mazco X/Y

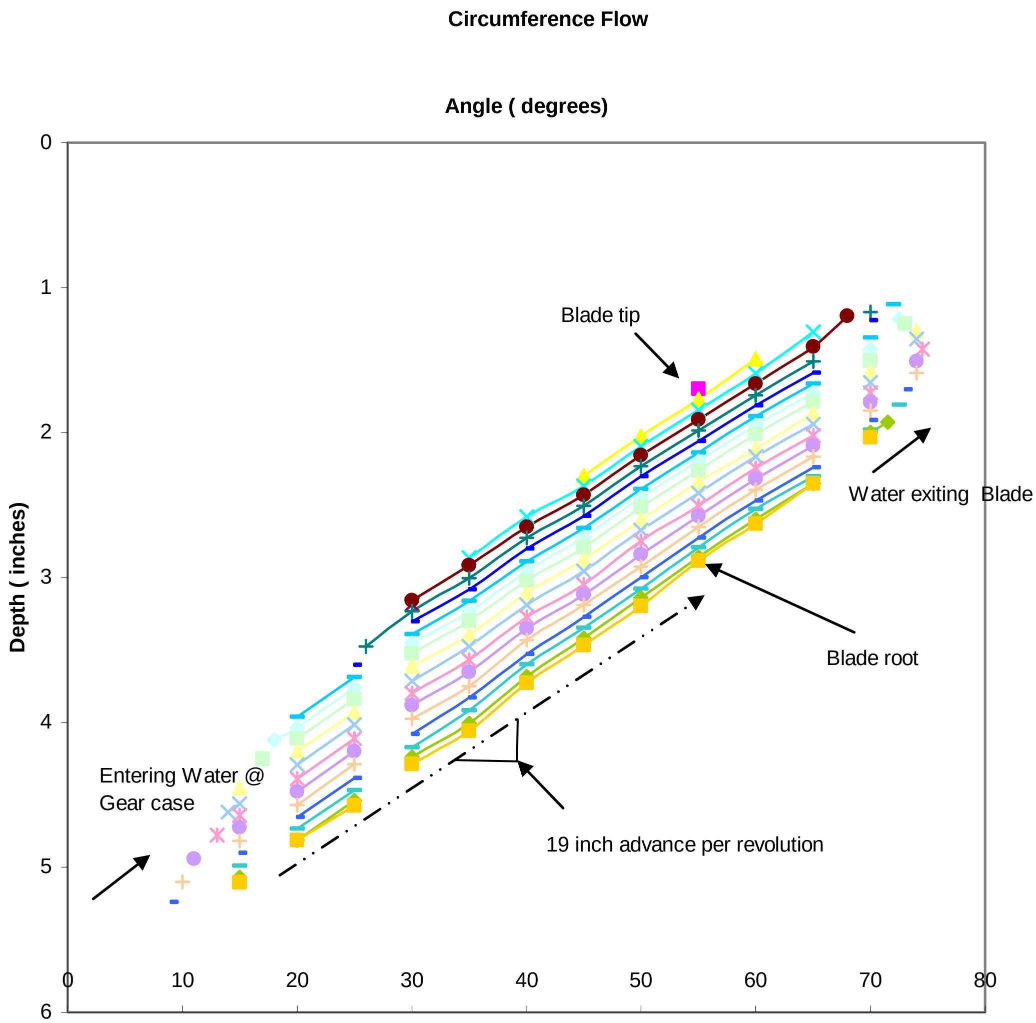

Table 3. Depth Vs angle.

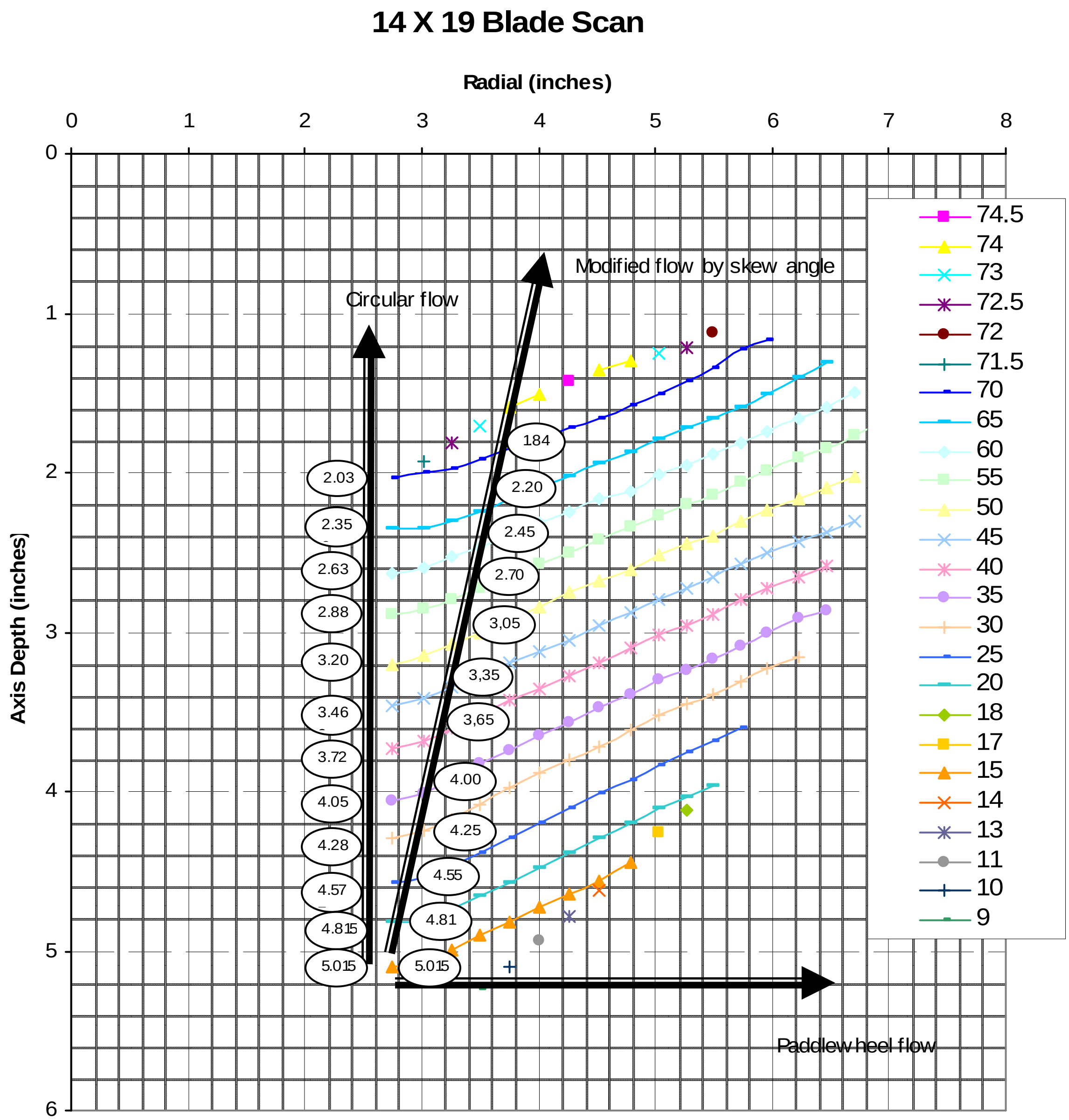

Table 4. Axis Vs Radial.

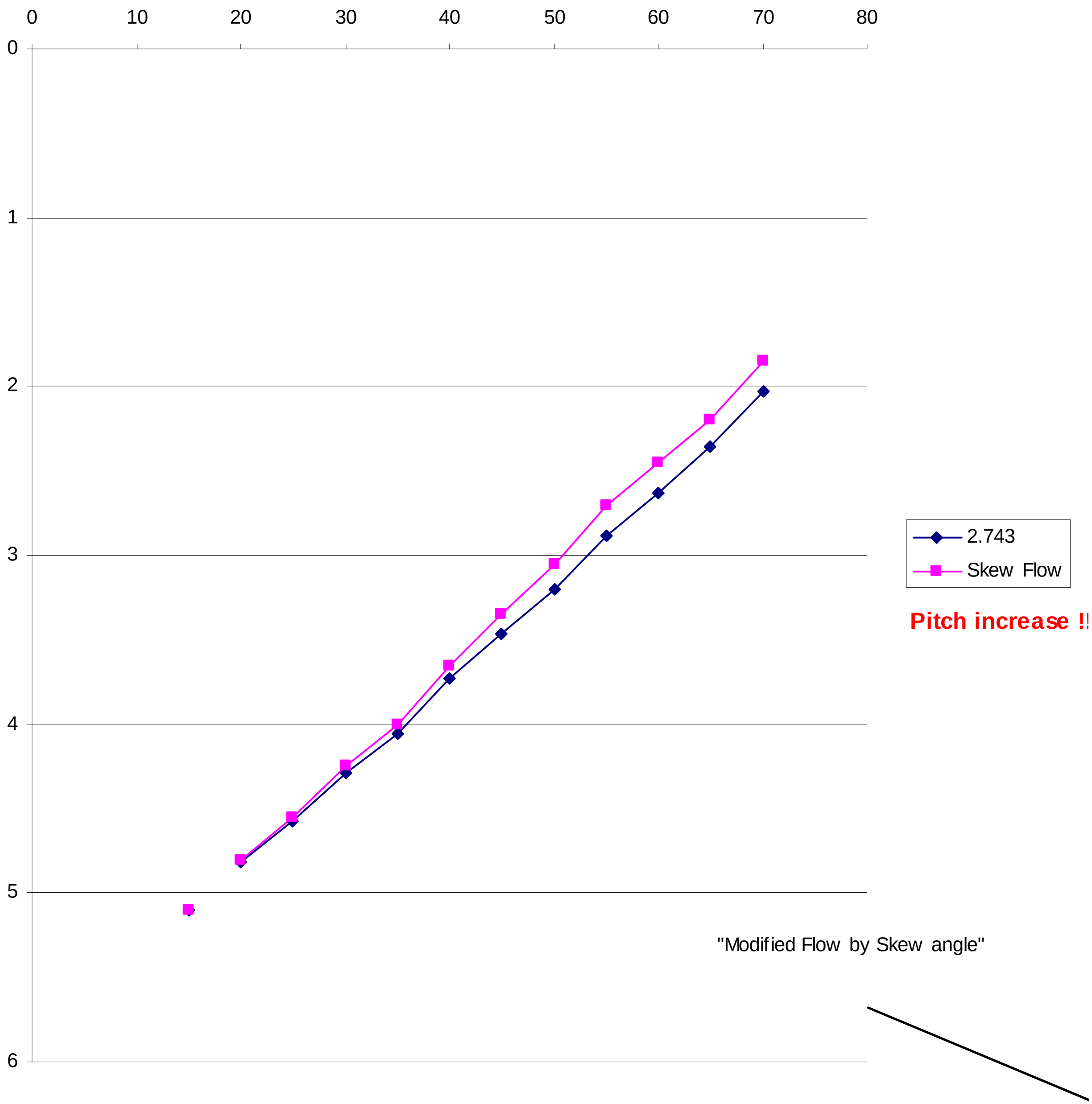

Table 5. Pitch increase vs. angle of attack

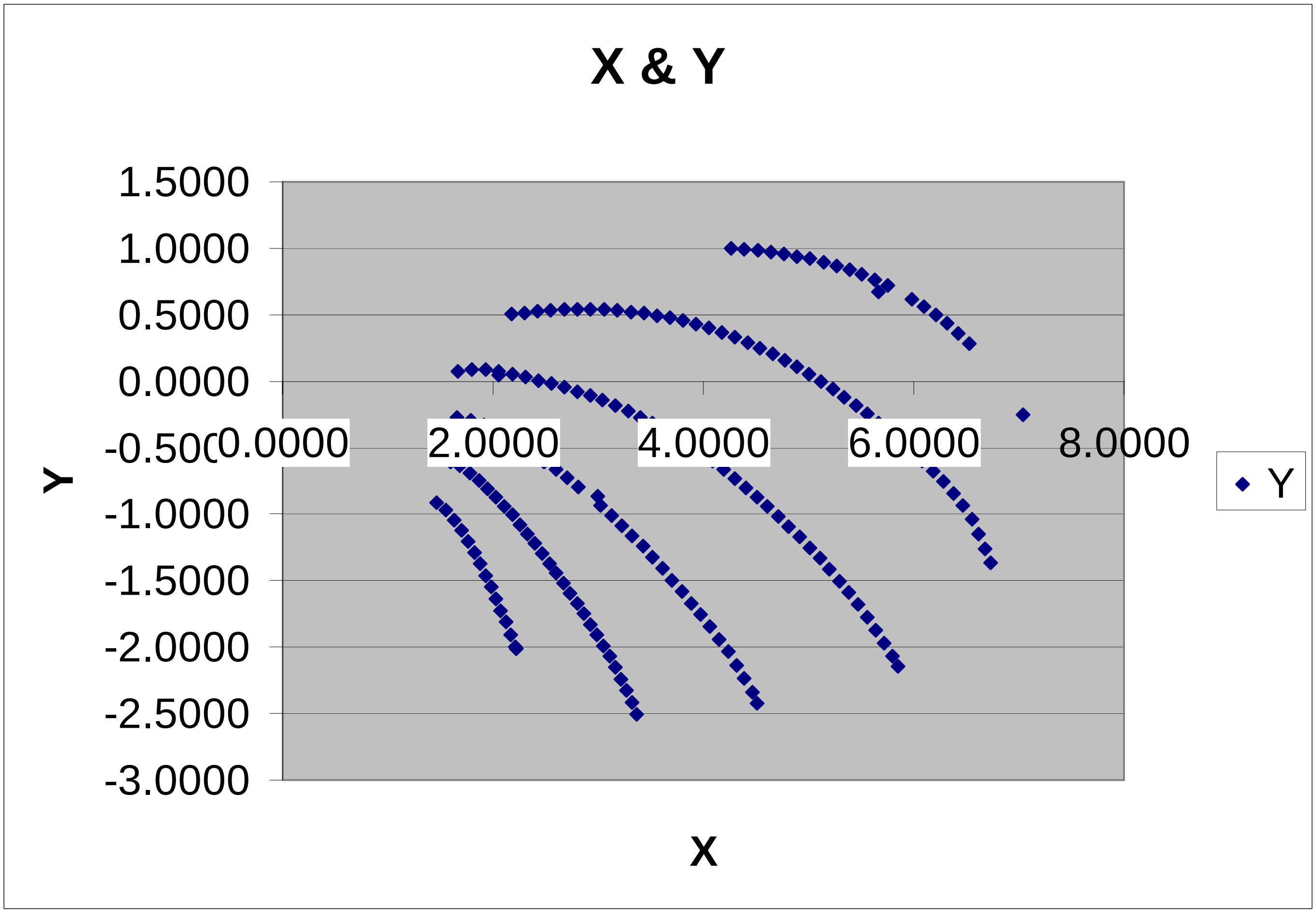

Table 6. Kennedy Space Center 28 pitch Mazco X/Y

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